Ninth International Conference on

Superlattices, Microstructures and Microdevices

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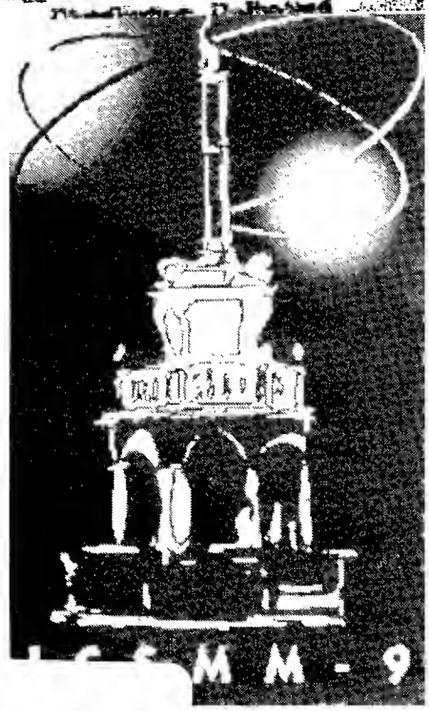

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DTIC QUALITY INSPECTED 3

Liège, Belgium
July, 14-19 1996

Abstract Workbook

Ninth International Conference on

Superlattices, Microstructures and Microdevices

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DTIC QUALITY INSPECTED 3

Sponsored by

- Le Gouvernement Wallon,
- Le Ministère de l'Education, de la Recherche et de la Formation de la Communauté Française de Belgique,
- La Province de Liège,
- La Ville de Liège,
- Le Fonds National de la Recherche Scientifique (FNRS),
- The European Research Office of the U.S. Army Research Development & Standardization Group,
- La Radio Télévision Belge de la Communauté Française (RTBF),
- L'Université de Liège (ULg),
- L'Electropôle,
- L'Association pour la Recherche Avancée en Microélectronique et en Intégration de Systèmes (ARAMIS).

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CONFERENCE INFORMATION

General information

The Ninth International Conference on Supperlattices, Microstructures and Microdevices (ICSMM-9) will be held from July 14 to July 19, 1996 in Liège, Belgium. All sessions will take place in the Conference Center (Palais des Congrès) facing the river Meuse in the center of the city of Liège. ICSMM-9 is being organized as a satellite conference of the 23rd ICPS, July 21-26, 1996 in Berlin, Germany.

Conference Administration

- Before the Conference :
  Chantal Lacrosse, Michèle Delville
  Conference Services
  A.I.M.
  31, rue Saint Gilles, B-4000 Liège (Belgium)
  Int. phone : + 32 41 222 946
  Int. fax : + 32 41 222 388
  E-mail : `aimulg@misc.ulg.ac.be`
- During the Conference : the Secretariat will be based at the Liège Conference Centre Palais des Congrès. Direct phone and fax numbers to the Secretariat will be given out at the time of the Conference.

Technical sessions

Full details of the programme of the technical sessions are given in the enclosed leaflet.

Oral presentations : will be held in the Reine Elisabeth Room (Queen Elisabeth) on the first floor of the Conference Centre in the immediate area of the registration desk.

In order to accommodate as many contributions as possible, as a consequence of the overwhelming number of submissions received, contributed papers for oral presentation will be allotted a total of 15 minutes (12 minutes plus 3 minutes discussion). At the rostrum, an overhead and a slide projectors will be available. Authors who have special visual aids requirements are asked to contact the secretariat in advance of the conference.

Invited paper presentations : will be scheduled for a total length of 30 minutes (25 minutes plus 5 minutes discussion).

Poster Sessions : will be held in the hall Grand Foyer in front of the Conference Room Queen Elisabeth according to the following timetable :

- Tuesday, 16 July from 17:00 to 19:00 hrs : session TuP
- Thursday, 18 July from 15:30 to 17:30 hrs : session ThP Display boards will be available (one per paper/white panel of 1.15 m wide and 1.50 m high). Authors are requested to put their material on display as follows :
- session TuP : from Monday afternoon
- session ThP : from Wednesday morning and to remove it immediately at the end of the relevant session.

Papers by title : the authors of this range of papers will be given the opportunity to discuss directly with participants during coffee breaks or immediately after lunch. A special meeting area will be arranged in the main hall Grand Foyer. Further information will be shown on a special board during the conference period.

Conference Literature

The abstracts of the Conference papers will be published in one bound volume. The Conference Proceedings will be published by Superlattices and Microstructures. A list of registrants will be issued at the Conference.

Manuscripts

Three copies of the manuscripts are due at the Conference and will be reviewed during the Conference. Invited papers are allowed a maximum of eight (8) pages, contributed oral, poster and papers per title are allowed a maximum of four (4) pages.

TEXuser may find the guidelines on the World Wide Webb at the Academic Press On Line Journal Library :

"http://www.idealibrary.com" or "http://www.europe.idealibrary.com"

Authors not familiar with TEXcould follow the format of instructions for publication in Physical Review B.

The accepted manuscripts will be published in "Superlattices and Microstructures".

Name Badge

An admission name badge will be provided for each participant which will authorize access to sessions and social events. It must be worn throughout the conference period.

Mail and Messages for Conference Participants

Messages for participants will be announced on a "black board" and will be collected from the welcome desk. However, participants cannot be called from the lecture room.

Registration

The registration fee is BEF 12500 for senior participants and BEF 10000 for students. The registration fee includes registration at ICSMM-9, the abstract workbook, the welcome reception and the conference banquet.

Payment

Payment for registration is required in advance of the Conference. Payment must be made in Belgian Francs (BEF) and payable to A.I.M. without any charges for the beneficiary.

- by bank transfer to générale de Banque, Liège, account nr. 240-0432230-02 of A.I.M.
- by credit card Visa or Eurocard/Mastercard only

Cancellation Policy

You may cancel your registration in writing (a faxed letter is acceptable) by June 15, 1996. Your registration will be refunded less a BEF 1.500 ($50) enrollment charge.

Insurance

The conference fee does not include any provision of insurance of participants against illness, personal accidents, thefts or damage of property. Participants are recommended to take their own insurance to cover these eventualities.

Confirmation

Confirmation of your registration will be e-mailed to you approximately 1 week after receipt of completed registration form. If you have not received such an acknowledgement, please call us to make sure that we have registered your booking.

Practical information

Venue

The Conference will be held at the Liège Convention Centre Palais des Congrès

Esplanade de l'Europe, 2, B-4020 Liège
Int phone : + 32 41 43 01 44
Int fax : + 32 41 43 20 85

Situated on the right bank of the River Meuse, in a romantic garden, the Centre is within quite easy walking distance from the city centre and most of the selected hotels. It is also served by bus routes operated by TEC from downtow (26/28/31) and from the Guillemins railway station (17).

Travel

Air: Travellers arrive at Brussels National Airport, about 100 km far away from Liège. Shuttle trains Airport City Express operate every 20 minutes between the airport

and the Brussels North Station (Bruxelles Nord/ Brussel Noord) from where direct trains to Liège (Guillemins Station) can be taken every hour at least between 6:00 to 24:00 hrs. Tickets to Liège may be purchased in the airport.

Rail: Liège is easily accessible from all major European cities via Liège-Guillemins railway station

Road: Liège is at the centre of an important motorway network. Car parking facilities are available beneath the Convention Centre and in the immediate vicinity.

Hotel Reservations

Participants wishing to book hotel accommodation are asked to fill out the registration form as appropriate and to return it by 30 June at the latest to the Conference Administrative Office.

Sunday Registration and Welcome Reception

Participants have the opportunity to register and meet up other attendees on Sunday, 14 July at the Conference Centre. The registration desk will be open between 17:30 - 20:30 hrs at the entrance of the hall Pas Perdus (ground-floor). Participants will be offered a buffet made of regional products and famous Belgian beers. The buffet will be open until 22:00 hrs. Ticket is included in each registration fee but please indicate on the registration form if you plan to attend. Additional tickets can be purchased at a price of BEF 500.

Participants will also have the possibility to enjoy a firework display which takes place each year on 14 July to celebrate the French National Day. It should start at about 23:00 on the opposite bank of the River Meuse.

Welcome breakfast

On Monday July 15, from 6:30 a.m. to 9:00 a.m., a welcome breakfast will be organized for all the participants in the "Palais des Congrès" (Convention Center) by the R.T.B.F. (French Speaking Radio-Television).

Registration - Enquiries

On Monday, Tuesday and Thursday, the registration desk will be open at the Convention Centre, 1st floor, from 8:00-18:00 hrs. On Wednesday and Friday, it will be open from 8:00-13:00 hrs. Participants are asked to check-in upon arrival at the Conference Centre. They will receive their personal pack, including conference literature and name badge.

There will be a special desk where participants and those accompanying them will be able to collect useful information regarding tourist facilities.

A bureau de change will also be open on Monday and Tuesday from 12:00 - 14:00 hrs (further information available from the welcome desk).

Refreshments

Morning and afternoon refreshments will be served each day in front of the Conference room at the times indicated in the programme, at around 10:30 hrs and 16:00 (when applicable).

Lunches

Lunches comprizing a cold dish, a dessert and a drink will be arranged on Monday, Tuesday and Thursday in the Conference Centre, hall Pas Perdus (ground floor). Tickets are to be purchased from the welcome desk. Price : BEF 550 or US $18.00. However, participants are asked to indicate if they plan to purchase lunch tickets in order to allow the organizers to take the required decisions (check as appropriate on the registration form). Very few restaurants or cafés are available in the immediate vicinity of the Conference Centre.

It is intended to distribute to each participants a list of recommended restaurants in different ranges of prices.

Conference Banquet

The Conference banquet will be organized in a somptuous 17th century restored barn at the Castle of Modave. It will be held on Thursday, 18 July at 19:30 hrs. Participants will

be given a chance to visit this beautiful castle built in classical style and proud of owing wonderful furniture.

One ticket is included in each full registration fee however participants are asked to indicate if they intend to participate. Additional tickets for accompanying persons have to be purchased in advance. The cost will be BEF 2000, (check the appropriate box on the registration form).

Transportation will be provided. Coaches will depart at 18:30 hrs and return at about 23:00 hrs. Further useful information will be given during the Conference.

Excursion to Bruges

It will be organized on Wednesday afternoon. Coaches will leave from the Conference Centre at 12:30 hrs. Each participant will receive a lunch box, as well as tourist information and a city map of Bruges. Departure from Bruges to Lige at 20:00 hrs. The journey lasts approximately two hours and a half.

Bruges is one of the Europe's loveliest cities, a romantic open-air museum of churches, elagant houses, famous canals, the one city in Belgium which is an absolute "must" for the tourist.

One ticket is included in each registration fee and if you want to participate, please thick the box on the registration form. The cost of an additional ticket will be BEF 700, to be purchased in advance.

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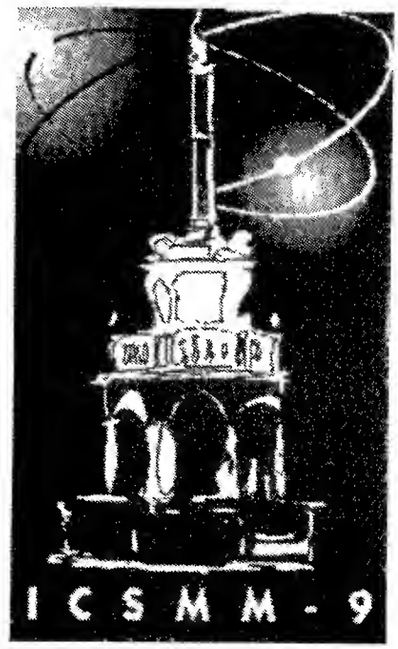

Liège, Belgium
July, 14-19 1996

Final Program

Monday, July 15	**Tuesday, July 16**	**Wednesday, July 17**	**Thursday, July 18**	**Friday, July 19**
Welcome Breakfast *6:30-9:00*				
Opening *9:00-9:15*	TuA *8:30-10:30*	WeA *8:30-10:00*	ThA *8:30-10:45*	FrA *8:30-10:15*
MoA *9:15-10:00*				
Coffee break - papers per title *10:00-10:30*	Coffee break - papers per title *10:30-11:00*	Coffee break *10:00-10:30*	Coffee break - papers per title *10:45-11:15*	Coffee break *10:15-10:45*
MoB *10:30-12:30*	TuB *11:00-12:30*	WeB *10:30-11:45*	ThB *11:15-12:30*	FrB *10:45-11:45*
Lunch *12:30*	Lunch *12:30*	Excursion to Brugge *12:00*	Lunch *12:30*	Closing remark *12:00*
MoC *13:30-15:30*	TuC *14:00-15:30*		ThC *14:00-15:15*	
Coffee break - papers per title *15:30-16:00*	Coffee break - papers per title *15:30-16:00*		Coffee break - papers per title *15:15-15:45*	
MoD *16:00-18:00*	TuD *16:00-17:00*		Poster Session *15:45-17:45*	
	Poster Session *17:00-19:00*			
Governor's reception *18:30*			Banquet *18:30*	

Monday, July 15

9:00 Opening

MoA Superconductor - semiconductor contacts

9:15-10:00 **chair : K. von Klitzing, Max-Planck Institute, Stuttgart**

9:15 **Induced superconductivity in *InAs* quantum wells with superconducting contacts**
MoA-1 H. Kroemer, *UC Santa Barbara (invited)*

9:45 **Low-dimensional electron transport properties in *InAs/AlGaSb* mesoscopic structures**
MoA-2 M. Inoue, T. Sugihara, T. Maemoto, S. Sasa, H. Dobashi and S. Izumiya, *Osaka Institute of Technology*

10:00 Coffee break - papers per title

MoB Intersubband processes in quantum wells and superlattices

10:30-12:30 **chair : F. Julien, CNRS Orsay**

10:30 **Interminiband electroluminescence and laser action in semiconductor superlattices**
MoB-1 G. Scamarcio, F. Capasso, J. Faist, C. Sirtori, A.L. Hutchinson, D. Sivco and A.Y. Cho
Lucent Technologies Bell Laboratories (invited)

11:00 **Optically pumped mid-infrared intersubband emission and lasing in coupled quantum wells**
MoB-2 A. Sa'ar , *The Hebrew university of Jerusalem (invited)*

11:30 **Intersubband scattering rates in *GaAs* quantum wells, measured by femtosecond luminescence**
MoB-3 M. Hartig, S. Haacke, B. Deveaud , *EPFL, Lausanne*
R.A. Taylor and L.Rota , *University of Oxford*

11:45 **Mid-infrared femtosecond spectroscopy of intersubband hot carrier relaxation in quantum wells**
MoB-4 P.M. Fauchet, Ju.V. Vandyshev, J.M. Russel, Z. Xu and G.W. Wicks, *University of Rochester*

12:00 **Energy relaxation of hot electrons in *GaAs/AlGaAs* superlattices measured by infrared differential spectroscopy**
MoB-5 W. Hilbert, M. Helm, *Universität Linz*
K. Alavi, R.N. Pathak, *University of Texas at Arlington*

12:15 **Quasistatic and dynamic interaction of high-frequency fields and miniband electrons in a semiconductor superlattice and intraminiband relaxation**
MoB-6 S. Winnerl, E. Schomburg, J. Grenzer, I. Lingott, H-J. Regl, A.A. Ignatov, A.D. Semenov, K.F. Renk
Universität Regensburg
D.G. Pavelev, Yu. Koschunirov, *Nizhny Novgorod State University*
B. Mezler, V. Ustinov, S. Ivanov, S. Schaposchnokov and P.S. Kop'ev, *Ioffe Institute*

12:30 Lunch

MoC Electronic and optical properties of quantum wells and superlattices

13:30-15:30 **chair : J.C. Woo, Seoul National University**

14:00 **Electron-hole hybridizing in $InAs$ single quantum wells clad with $GaSb$**
MoC-1 R.J. Wagner, B.V. Shanabrook, M.J. Yang and J.R. Waterman, *Naval Research laboratory*

14:15 **Coupled utltrathin $InAs$ layers in $GaAs$ as a tool for the determination of band offsets**
MoC-2 J. Brübach, A.Yu. Silov, J.E.M. Haverkort, W. v.d. Vleuten and J.H. Wolter
Eindhoven University of Technology

14:30 **Quasibound states induced by $AlAs$ monolayers in $(In,Ga)As/GaAs$ quantum wells**
MoC-3 C.D. Lee and S.K. Noh, *Korea Research Institute of Standards and Science*
K-S. Lee, *ETRI, Taejon, Korea*

14:45 **Extremely flat interfaces in $In_{0.04}Ga_{0.96}As/Al_{0.3}Ga_{0.7}As$ quantum wells grown on (411)A**
MoC-4 **$In_{0.04}Ga_{0.96}As$ substrates by MBE**
S. Hiyamizu, T. Saeki, T. Motokawa, S. Shimomura, T. Kitada, *Osaka University*
A. Adachi, *Nissin Electric Co. ltd.*
Y. Okamoto, *Kubota Ltd.*
T. Kusunoki, K. Nakajima, *Fujitsu Labs. Ltd.*
N. Sano, *Kwansei-Gakuin University*

15:00 **Detailed balance between impact ionization and Auger recombination of trions in**
MoC-5 **photoexcited $GaAs/AlAs$ quantum wells**
A. Manassen, E. Cohen, Arza Ron, E. Linder, *Technion, Israel Institute of technology*
L.N. Pfeiffer, *AT&T Bell Laboratories*

15:15 **Bistability and quantisation of continuum states in piezo-electric quantum wells**
MoC-6 L.R. Wilson, D.J. Mowbray, M.S. Skolnick, D.W. Peggs, G.J. Rees, R. Grey, G. Hill and M.A. Pate
University of Sheffield

15:30 **Stimulated emission in $Zn_{1-x}Cd_xSe/ZnSe$ quantum wells : Exciton, biexciton and**
MoC-7 **free-carrier recombinations**
L.Calcagnile, D. Greco, G. Coli and R. Cingolani, *Universita'di Lecce*
M.Lomascolo and M. Di Dio, *Centro nazionale ricerca e sviluppo materiali (PASTIS-CNRSM)*
L. Sorba and A. Franciosi, *INFM*

15:45 **Role of localized excitons in the stimulated emission in ultra thin $CdSe/ZnSe/ZnSSe$ single**
MoC-8 **quantum well structures**
S. Yamagushi, H. Kurusu, Y. Kawakami, Shizuo Fujita and Shigeo Fujita, *Kyoto University*

15:30 Coffee break - papers per title

MoD Transport and localization in 2-D systems

16:00-18:00 **chair : J.T. Devreese, University of Antwerp**

16:30 **Compressibility measurements of two-dimensional electron gases**
MoD-1 N.K. Patel, *Toshiba Cambridge Research Centre*
I.S. Millard, *University of Cambridge*
C. Foden, *Toshiba Cambridge Research Centre*
E.H. Linfield, D.A. Ritchie, *University of Cambridge*
M. Pepper, *Toshiba Cambridge Research Centre*

16:45 **Capacitance spectroscopy of compressible and incompressible stripes in a narrow electron**
MoD-2 **channel**
D. Schmerek, S. Manus, *Ludwig-Maximilians-Universität*
A.O. Govorov, *Institute of semiconductor physics, Novosibirsk*
W. Hansen, J.P. Kotthaus, *Ludwig-Maximilians-Universität*
M. Holland, *University of Glasgow*

17:00 **The interplay of the periodic potential and electron-electron scattering in surface**
MoD-3 **superlattices**
A. Messica, U. Meirav, Ady Stern, H. Sthtrikman, V. Umansky and D. Mahalu, *Weizmann Institute*

17:15 **Spin-dependent hole delocalization enhancement by bandfilling effects in degenerate**
MoD-4 **asymmetric double quantum wells**
M. Kemerink, P.M. Koenraad, *Eindhoven University of Technology*
P.C.M. Christianen, A.K. Geim, J.C. Maan, *High-field magnet laboratory, Nijmegen*
J.H. Wolter, *Eindhoven University of Technology*
M. Henini, *University of Notthingham*

17:30 **Nonlinear impurity screening and metal insulator transition in strongly depleted 2D electron**
MoD-5 **gases**
K. Schrüfer, *Universität Erlangen*
C. Metzner, *University of Tokyo*
M.Ch. Hofmann and G.H. Döhler, *Universität Erlangen*

17:45 **Transport properties of a high mobility electron gas formed in a $Ga_{0.25}In_{0.75}As/InP$**
MoD-6 **quantum well containing line dislocations**
P.Ramvall, N. Carlsson, P. Omling, L. Samuelson and W. Seifert, *Lund University*

18:00 **Spatial correlation effects of charged impurities on electron mobility in δ-doped $GaAs$**
MoD-7 J.M. Shi, *Universiteit Antwerpen and Technische Universiteit Eindhoven*
P.M. Koenraad, A.F.W. van de Stadt, *Technische Universiteit Eindhoven*
F.M. Peeters, *Universiteit Antwerpen*
J.T. Devreese, *Universiteit Antwerpen and Technische Universiteit Eindhoven*
J.H. Wolter, *Technische Universiteit Eindhoven*

18:15 **Free electron laser saturation spectroscopy of neutral donors and negative donor ions**
MoD-8 **confined in $GaAs/AlGaAs$ quantum wells**
S.R. Ryu, G. Herold, J. Kono, M. Salib, B.D. McCombe, *SUNY at Buffalo*
J. Kaminski, S.J. Allen Jr., *UC Santa Barbara*

18:30 **Governor's reception**

Tuesday, July 16

TuA Tunneling in quantum dots

8:30-10:30 **chair : J.C. Portal, INSA Toulouse**

8:30 **Self-organized growth of quantum dot-tunnel barrier systems**
TuA-1 M. Dilger, *Max-Planck Institute, Stuttgart (invited)*

9:00 **Modelling of inter-dot Coulomb interaction effects in field-effect transistors with embedded**
TuA-2 **quantum dot layer**
C. Metzner, G. Yusa and H. Sakaki, *University of Tokyo, RCAST*

9:15 **Random telegraph signal in tunneling transport through a single 0-D impurity state**
TuA-3 M.R. Deshpande, R.G. Wheeler, M.A. Reed, *Yale University*
R.J. Matyi, *Texas Instrument Inc., Dallas, TX*

9:30 **Resonant photon assisted tunneling in a coupled quantum dot system**
TuA-4 T. Fujisawa and S. Tarucha, *NTT Basic research labs. (invited)*

10:00 **Magnetotunneling spectroscopy in a single *AlAs* barrier incorporating *InAs* quantum dots**
TuA-5 A. Thornton, I.E. Itskevich, T. Ihn, M. Henini, P. Moriarty, A. Nogaret, P.H. Beton, L. Eaves, P.C. Main
University of Nottingham

10:15 **Memory effect double-barrier resonant tunnel diode with *InAs* dots observed at room**
TuA-6 **temperature**
K. Yoh and T. Nakano, *Hokkaido University*

10:30 **Coffee break - papers per title**

TuB Optical processes and luminescence in quantum dots

11:00-12:30 **chair : R. Planel, CNET Bagneux**

11:00 **Luminescence and magneto-luminescence sprectroscopy of *InAs* self-assembled quantum dots**
TuB-1 P.D. Wang, J.L. Merz, *University of Notre Dame*
G. Medeiros-Ribeiro, M. Oestreich, P.M. Petroff, *UC Santa Barbara*
H. Akiyama, H. Sakaki, *University of Tokyo, RCAST*

11:15 **Time-resolved photoluminescence of excited states in $In_{1-x}Ga_xAs/GaAs$ self-assembled**
TuB-2 **quantum dots**
S. Raymond, S. Fafard, P.J. Poole, A. Wojs, P. Hawrylak, S. Charbonneau, *NRCC*
D. Leonard, R. Leon, P.M. Petroff and J.L. Merz, *UC Santa Barbara*

11:30 **Composition and strain of self-assembled *(In, Ga, Al)Sb/(Ga, Al)As* quantum dots**
TuB-3 B.R. Bennett, B.V. Shanabrook, E.R. Glaser, R. Magno and M.E. Twigg, *Naval Research Lab., Washington*

11:45 **Excited-state luminescence from vertically-stacked and electronically-coupled *InAs* pyramids**
TuB-4 **in *GaAs***
M.S. Miller, L. Landin, M.E. Pistol, P. Castrillo, C. Pryor, B. Kowalski, S. Jeppesen and L. Samuelson
Lund University

12:00 **Carrier relaxation and thermal activation of localized excitons in self-organized *InAs***
TuB-5 **quantum dots**
Z.Y. Xu, Z.D. Lu, X.P. Yang, Z. L. Yuan, B.Z. Zheng, J.Z. Xu and W. Zhang
Institute of Semiconductors, Academy Sinica
W.K. Ge, Y. Wang, J. Wang and L.L. Chang, *Hong Kong University of science and technology*

12:15 **Radiation characteristics of injection lasers based on vertically coupled quantum dots**
TuB-6 S.V. Zaitsev, N.Y. Gordeev, Y.M. Sherniakov, V.M. Ustinov, A.E. Zhukov, A.Y. Egorov, N.N. Ledentsov, M.V. Maximov, *Ioffe Institute*
D. Bimberg, *Technische Universitat Berlin*
P.S. Kop'ev and Zh.I. Alferov, *Ioffe Institute*

12:30 Lunch

TuC Magnetotransport in mesoscopic systems

14:00-15:30 **chair : S. Bandyopadhyay, University of Nebraska**

14:00 **Quantization and confinement phenomena in superconducting microstructures and**
TuC-1 **superlattices**
V.V. Moshchalkov, *KU Leuven (invited)*

14:30 **Step-like mesoscopic conductance in inhomogeneous magnetic fields**
TuC-2 Y. Lyanda-Geller, P.M. Goldbart, *University of Illinois at Urbana-Champaign*
D. Loss, *Simon Fraser University*

14:45 **Universal conductance fluctuations in a random magnetic field**
TuC-3 G.M. Gusev, *Universidade de Sao Paulo*
X. Kleber, *CNRS-LCMI and INSA-Toulouse*
U. Gennser, *Paul Scherrer Institute*
D.K. Maude, *CNRS-LCMI*
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J.C. Rossi, *Universidade fedral da Sao Carlos*
Yu.V. Nastaushev, *Russian academy of sciences*

15:00 **Magnetometry of mesoscopic superconductors**
TuC-4 A.K. Geim, S.V. Dubonos, J.G.S. Lok and J.C. Maan, *University of Nijmegen (invited)*
X.Q. Li anf F.M. Peeters, *University of Antwerpen*

15:30 Coffee break - papers per title

TuD Chaos in nanostructures

16:00-17:00 **chair : B. MacCombe, Suny Buffalo**

16:00 **Ballistic conductance fluctuations in quantum dots**
TuD-1 C. Marcus, *Stanford University (invited)*

16:30 **Scaled field studies of quantum chaotic states in wide potential wells**
TuD-2 P.B. Wilkinson, A. Thornton, T.M. Fromhold, T.J. Foster, L. Eaves, F.W. Sheard, P.C. Main, M. Henini *University of Notthingham*

16:45 **Transition between synchronization and spatio-temporal chaos in doped *GaAs/AlAs***
TuD-3 **superlattices**
Y. Zhang, R. Klann, H.T. Grahn, K.H. Ploog, *Paul-Drude institut für Festkörperelektronik*

TuP Poster session

17:00-19:00

TuP-1 **Hopping transport in superlattices**
S. Rott, N. Linder, and G.H. Döhler
Institut für Technische Physik, Universität Erlangen, Erwin-Rommel-Str.

TuP-2 **Anderson and Stark localization in GaAs/(AlGa)As disordered superlattices**
G.F. Lorusso, *EPFL, Lausanne*, V. Capozzi, *Univ. di Bari,*
F. Tassone, J.L. Staehli, D. Martin, *EPFL, Lausanne*

TuP-3 **Field induced interlayer interband coupled states in aperiodic InAs/GaSb heterostructures**
Gyungock Kim, *ETRI, Taejon*

TuP-4 **Carbon-based superlattices of new type**
A. Baranov, *Res. Inst. of Vac. Tech. Moscow*
P. Kondrashov, *Moscow State Inst. of Elec and Math.*
I. Smirnov, *Inst. of Radio Eng. and Elec. of Russian Acad. of Science*
Tereshin, *Res. Inst. of Vac. Tech. Moscow*

TuP-5 **Interlayer spin coherence in antiferromagnetic EuTe/PbTe superlattices observed by polarized neutron diffraction**
V. Nunez, *NIST, Gaithersburg*, G. Springholz, *Johannes Kepler Univ. Linz*
T.M. Giebultowicz, H. Kepa, K.I. Goldman, *Oregon State Univ.*
C.F. Majkrzak, *NIST, Gaithersburg*, G. Bauer, *Johannes Kepler Univ. Linz*

TuP-6 **In-plane optical anisotropy of (N11) GaAs/GaAlAs superlattices**
Z. Yang, Yongning Sheng and Y.Q. Wang, *Hong Kong Univ. of Sci. and Tech.*

TuP-7 **Atomic layer epitaxy of II-VI semiconductor heterostructures**
J.M.Hartmann, H.Mariette, F.Kany, M.Charleux, J.L.Rouvière and H.Ulmer-Tuffigo
CEA-Grenoble France

TuP-8 **Photoluminescence Internal Quantum Yield in Superlattices**
D. Martins, C. Gourdon, P.Lavallard, *Univ. Paris*
R. Planel, *L2M, CNRS, Bagneux*

TuP-9 **Photoreflectance measurements in GaAs-AlGaAs asymmetric quantum wells**
M.A.G. Soler, P.C. Morais and J. Depeyrot, *Universidade de Brasilia*
J.A.N.T. Soares, *Universidade de São Paulo*
G. Weimann and G. Trankle, *Tecnische Universitat Munchen*

TuP-10 **Excitonic molecules in type-II superlattices**
Takuma Tsuchiva, Shin'ichi Katayama, *JAIST, Tatsunokuchi, Japan*
Tsuneya Ando, *Univ. of Tokyo*

TuP-11 **Anomalies in the exciton photoluminescence polarization of short-period superlattices with corrugated interfaces**
V.G.Litovchenko, D.V.Korbutyak, S.G.Krylyuk, Yu.V.Krynchenko
Nat. Acad. of Sci. Ukraine
H.T. Grahn and K.H. Ploog, *Paul-Drude-Inst. für Festkörperelec, Berlin*

TuP-12 **Interwell excitons in GaAs superlattices**
D.Birkedal, K.El.Sayed, G.Sanders, C.Spiegelberg.V.G. Lyssenko, C.Stanton and J.M. Hvam
Tech. Univ. of Denmark
V.B. Timofeev, *Russian Acad. of Sci.*, M. Bayer, *Univ. Würzburg*

TuP-13 **Combined exciton-electron excitation in quantum wells with electron gas of low density**
V.P.Kochereshko, D.R.Yakovlev, R.A.Suris, *A.F. Ioffe PTI*
W.Ossau, A.Waag, G.Landwehr, *Univ. Würzburg*
P.M.C. Christianen and J.C.Maan, *Univ. of Nijmegen*

TuP-14 **Magnetoexcitonic oscillations of ground and excited states in asymmetric quantum well structures**
A.R. Alves, *Univ. Federal de Vicosa, Brazil*
L.A.Cury, P.S.S.Guimarães and M.V.B.Moreira, *ICEX, UFMG, Belo Horizonte*

TuP-15 **Photoluminescence excitation spectroscopy on excitonic states of narrow GaAs-AlGaAs single quantum wells in high magnetic field**
H.S. Ko, Y.M.Kim, W.S.Kim, D.H.Kim, Y.S.Kim, J.C.Woo, *Seoul Nat. Univ*
T. Schmiedel, *Nat. High Mag. Field Lab. Florida*

TuP-16 **Rapid radiative decay of excitons in GaAs/AlGaAs QWs with extremely flat interfaces grown on a (411)A GaAs substrate by MBE**
S. Shimomura, K.Shinohara, *Osaka Univ.*, A.Adachi, *Nissin Elec. Co. Kyoto*
Y. Okamoto, *Res. and Headquarters Kubota LTD*, N. Sano, *Kwansei Gakuin Univ.*
M. Hosoda, K. Fujita, T. Watanabe, *ATR Optical and Radio Comm. Res. Lab. Kyoto*

TuP-17 **Optical studies of localized excitons in symmetric coupled quantum wells**
R.J.Stone, J.G.Michels, D.Kinder, C.C.Chang, *Clarendon Lab. Oxford*
J.S.Roberts, *EPSRC III-V Semicond. Facility UK*
R.J.Nicholas, A.M.Fox, *Clarendon Lab. Oxford*

TuP-18 **Exciton-assisted tunneling transport in the heterojunction microstructures**
Simon M. Cao and M. Willander, *Linköping Inst. of Tech. Sweden*

TuP-19 **Tunnel devices are not yet manufacturable**
V.A.Wilkinson and M.J.Kelly, *Univ. of Surrey, Guildford UK*

TuP-20 **Dependence of parallel hole mass on quantum well width barrier parameters and wave function localization**
U.Ekenberg, *Royal Inst. of Tech. Sweden*
A. Ghiti, *University of Newcastle, UK*

TuP-21 **Resolution of the out-of-zone solution problem in envelope function theory**
M.G.Burt, BT labs, Martlesham Heath, *Ipswich, IP5 7RE, UK*

TuP-22 **Valence band spectrum in pseudomorphically strained würtzite quantum wells**
Yu.M.Sirenko, J.B.Jeon, K.W.Kim and M.A.Littlejohn, *North Carolina State Univ.*
M.A. Stroscio, *ARO, North Carolina*

TuP-23 **Electron channel with high carrier mobility at the interface of isotype II broken-gap p-GaInAsSb/p-InAs single heterojunctions**
M.P.Mikhailova, T.I.Voronina, T.S.Lagunova, K.D.Moiseev, S.A.Obukhov, A.E.Rozov and Yu.P.Yakovlev, *Ioffe PTI*

TuP-24 **A novel secular equation for the superlattice envelope function formalism and application to the calculation of the electronic structure of Type-II InAs/$In_xGa_{1-x}Sb$ superlattices**
F. Szmulowicz, *Univ. of Dayton Res. Inst.*

TuP-25 **Electronic structure of (311)-InAs monolayers in GaAs**
Toshio Saito, *Univ. of Tokyo*

TuP-26 **Identification of zone boundary and interface phonon recombinations in photoluminescence from type II GaAs/AlAs Short Period Superlattices**
T. Gilmour, P.C. Klipstein, *Clarendon lab. Oxford*
W.R. Tribe, *Univ. of Sheffield UK*, G.W.Smith, *Defence Res. Agency UK*

TuP-27 **"Folded" Acoustic modes in III-V alloys with CuPt atomic ordering**
A.Hassine, J.Sapriel, P.Le Berre *France Telecom, Bagneux*
Y.Monteil, *Univ. Claude Bernard, Villeurbanne, France*

TuP-28 **Fano-like electron-phonon interference in delta-doped GaAs superlattices**
Yu.A.Pusep, M.T.O.Silva,*DF-Univ. Federal de São Carlos, Brazil*
S.W. da Silva, *Univ. de São Carlos, Brazil*
J. C. Galzerani, *DF-Univ. Federal de São Carlos, Brazil*
L.M.R.Scolfaro, R.Enderlein, A.A.Quivy, A.P.Lima and J.R.Leite
Univ. de São Paulo, Brazil

TuP-29 **Optical-phonon tunneling and the barrier interface mode**
B.K.Ridley, O.Al-Dossary, M.Babiker and N.A. Zakhleniuk, *Univ. of Essex*

TuP-30 **Photoconductivity nonlinearity at high excitation power in quantum well infrared photodetectors**
M.Ershov, *Univ. of Aizu*, H.C. Liu,*NRC Canada*
V.Ryzhii, *Univ. of Aizu*

TuP-31 **Two-dimensional quantum well infrared photodetector arrays**
H.C.Liu, Jianmeng Li, M.Buchanan and Z.R.Wasilewski, *NRC Canada*

TuP-32 **Valence band structure and optical absorption in p-type multiple quantum well infrared photodetectors under an applied electric field**
R.Melliti, P.Tronc, J.Depeyrot,
Ecole Supérieure de Phy. et Chimie Industrielles, Paris
E.Mao, A.Majerfeld
Univ. of Colorado, Boulder

TuP-33 **Intersubband Electro-Optical Modulators for near and mid infrared applications**
A. Sa'ar, R.Kapon, and A.Segev,*The Hebrew Univ. of Jerusalem*

TuP-34 **The role of higher energy bands in hot carrier transport investigated by electroluminescence spectroscopy**
J.W.Cockburn, J.J.finley, *Univ. of Sheffield*,
P.Winiewski, *Unipress Polish Acad. of Sci.*
R.Teissier, *L2M, CNRS, 92225 Bagneux Cedex, France*
M.S.Skolnick, *Univ. of Sheffield*
R.Grey, G.Hill, M.A.Pate, *EPSRC Central Facility for III-V Materials*

TuP-35 **Numerical evaluation of energy loss rate for hot carriers in quantum wells**
KunHuang, Bang-fen Zhu and Jian-zhong Zhang, *Chinese Acad. of Sci, Beijing*

TuP-36 **Photogalvanic effects in asymmetric quantum wells and superlattices**
H.Schneider, S.Ehret, C.Schönbein, K.Schwarz, G.Bihlmann and J.Fleissner
Fraunhofer-Inst. für Angewandte Festkörperphysik, Freiburg

TuP-37 **Multiple wavelength electroluminescence and laser generation in P-I-N resonant tunneling heterostructures**
A.A.Toropov, T.V.Shubina, A.V.Lebedev, B.Ya.Mel'tser, S.V.Shaposhnikov, M.G.Tkatchman and P.S.Kop'ev, *A.F. Ioffe PTI*
Y.Fu and M. Willander, *Linköping Univ.*

TuP-38 **Exciton dynamics in quantum well microcavities**
B.Sermage, S.Long, H.Eskinazi, M.Stellmacher,*France Telecom, CNET, PAB, Bagneux*
J.Bloch, V.Thierry-Mieg, *L2M, CNRS, BP107, 92225 Bagneux*
J.Y. Marzin, *France Telecom. CNET, PAB, Bagneux*
R.Planel, *L2M, CNRS, BP107, 92225 Bagneux*

TuP-39 **Theory of light emission from inhomogeneously broadened excitons in semiconductor microcavities**
V.Savona, *Inst. de Phy., EPFL, Lausanne*
C.Weisbuch, *Lab. de Phy. de la Matière Condensée, EcolePolytech. France*

TuP-40 **Relaxation of microcavity polaritons**
J.Wainstain, G.Cassabois, Ph.Roussignol, C.Delalande, M.Voos, *ENS, Paris*
F.Tassone, R.Houdré, R.P.Stanley and U.Oesterle,*EPFL, Lausanne*

TuP-41 **Emission of interface modes by dipoles in photonic crystals**
M.Babiker, A.Kamli, N.Enfati and A.Al-Hajry, *Univ. of Essex*

TuP-42 **Photonic band gap effects in a solid state cluster lattice**
E.P.Petrov, A.N.Rubinov, *Acad of Sci. of Belarus*
V.N.Bogomolov, A.V.Prokofiev, S.M.Samoilovich, *A.F. Ioffe PTI*
A.M.Kapitonov, I.N.Germanenko and S.V.Gaponenko, *Acad of Sci. of Belarus*

TuP-43 **Transmittance antiresonances, longitudinal resonances, and large photonic gaps in periodically modulated waveguides**
P.Vasilopoulos, *Concordia Univ. Quebec*
R.Akis, *Arizona State Univ. Tempe*

TuP-44 **X+ excitons in CdTe-CdMgTe modulation-doped quantum wells**
Y.Merle d'Aubigné, A.Haury, A.Arnoult, V.A.Chitta, J.Cibert, S.Tatarenko, A.Wasiela, *CNRS et Univ. Joseph Fourier, France*

TuP-45 **Excited states of the negatively charged exciton X- in wide modulation-doped CdTe/CdZnTe quantum wells**
K.Kheng, R.T.Cox, L.Gauthier, *CEA-Grenoble/DRFMC*
T.Baron, *CNRS et Univ. Joseph Fourier, Grenoble*

TuP-46 **In-well screening of the piezoelectric field in <111> CdTe/CdMnTe quantum wells by photogenerated carriers**
E.Vanelle, D.Block, J.Cibert and R.Romestain, *Univ. J. Fourier de Grenoble, France*
J.P.Likforman, A.Alexandrou, *ENSTA-Ecole Polytech. CNRS France*

TuP-47 **Coherent patterns and self-focusing of electrons by a thin nonlinear barrier**
O.M.Bulashenko, V.A.Kochelap, *Nat. Acad. Sci, Ukraine*
L.L.Bonilla, *Univ. Carlos III de Madrid, Butarque*

TuP-48 **Carrier spin-polarization near the fermi level in n-modulation doped AlGaAs/InGaAs/GaAs quantum well**
A.L.C.Triques, F.Iikawa, *IFGW-UNICAMP*,
M.Z. Maialle, *DFFA-Univ. São Francisco*
J.A. Brum, R.G. Pereira, *IFGW-UNICAMP*, G.Borghs, *IMEC, Leuven*

TuP-49 **Resonant tunneling between localized and extended states in coupled quantum elbows**
T.M.Fromhold, *Univ. of Nottingham*, P. Hawrylak, *NRC Canada*
A.Nogaret, M.J.Gompertz, P.C.Main, L.Eaves, F.W.Sheard and P.B.Wilkinson
Univ. of Nottingham

TuP-50 **Spin-orbit interaction sign manifestation in quantum cylinder conductance**
A.V.Chaplik, D.A.Romanov, L.I.Magarill, *Novosibirsk*

TuP-51 **Photovoltaic effects in a submicron ballistic ring**
A.A.Bykov, L.V.Litvin, N.T.Moshegov, A.I.Toropov, *Novosibirsk*

TuP-52 **Magneto-transport of electrons in a non-homogeneous magnetic field**
S.M.Badalian, I.S.Ibrahim and F.M.Peeters *Univ. of Antwerp, Belgium*

TuP-53 **Mesoscopic conductance fluctuations of a two-dimensional electron gas in a one-dimensional lattice of antidots**
M.V.Budantsev, Z.D.Kvon, A.G.Pogosov, L.V.Litvin, *Novosibirsk*

TuP-54 **The ultimate scaling limit of semiconductor-based transistors**
W.Zhang, C.H.Yang, *Univ. of Maryland*
M.J.Yang, *NRL Washington DC*

TuP-55 **Designing delta-doped quantum well structures suitable for power FET applications**
J.M.Roberts, J.J.Harris, *Semicond. IRC*, M.Hopkinson, *Univ. of Sheffield*
C.Roberts, *Imperial College*

TuP-56 **Multistable current-voltage characteristics as fingerprints of growth-related imperfections in semiconductor superlattices**
G.Schwarz, M.Patra, F.Prengel and E.Schöll, *Tech. Univ. Berlin*

TuP-57 **Electron channel with high carrier mobility at the interface of isotype II broken-gap p-GaInAsSb/p-InAs single heterojunctions**
M.P.Mikhailova, T.I.Voronina, T.S.Lagunova, K.D.Moiseev, S.A.Obukhov, A.E.Rozov and Yu.P.Yakovlev, *A.F.Ioffe PTI*

TuP-58 **Light-hole resonant tunneling through tensile-strained GaInAs quantum wells**
J.F.Lampin, X.Wallart, J.P.Gouy and F.Mollot, *IEMN, Villeneuve d'ascq, France*

TuP-59 **Probing nonparabolic conduction subbands in nanoscale InGaAs/InAlAs quantum wells with cyclotron resonance in very high magnetic fields**
N. Kotera, *Kyushu Inst. of Tech.*, Y.Shimamoto,H.Arimoto, *ISSP, Univ. of Tokyo*, K.Tanaka,*Kyushu Inst. of Tech.*
T.Mishima, *Central Res. Lab. Hitachi*, N.Miura, *ISSP, Univ. of Tokyo*

TuP-60 **Transport of hot electrons in quasi-continuum above multi quantum-well structures**
S.Maimon, E.Finkman, G.Bahir, and S.E.Schacham, *Technion, Isreal*

TuP-61 **Design and modeling of PbTe wide quantum wells based on n-i-p-i concept**
G.Span, P.Ganitzer, G.Heigl, A.Homer, J.Oswald, *Univ. of Leoben*

TuP-62 **Millimeter-wave negative differential conductance in GaInAs/AlInAs semiconductor superlattices**
C.Minot, N.Sahri, Le Person, J.F.Palmier, J.C.Harmand and J.C.Esnault
CNET/PAB, Bagneux

TuP-63 **Negative differential conduction in Bloch oscillations regime in hexagonal silicon carbide polytypes 4H, 6H and 8H**
V.Sankin, I.Stolichnov, *A.F.Ioffe PTI*

TuP-64 **Virtual states, absolute negative conductivity and multiphoton-assisted tunneling in semiconductor superlattices**
B.J. Keay, S.Zeuner, C.Aversa, S.J.Allen Jr.,*UCSB*
J.Galán, *Ohio State Univ.*
K.L.Campman, K.D.Maranowski, A.C.Gossard, U.Bhattacharya, M.J.W.Rodwell, *UCSB*

TuP-65 **Observation of sequential excited-to-excited states resonant tunneling in weakly coupled superlattices with wide quantum wells**
Yu.A.Efimov, Yu.A.Mityagin, V.N.Murzin, G.K.Rasulova,*P.N.Lebedev Phy. Inst. Moscow*

TuP-66 **Microscopic modeling of field domains in superlattices**
Andreas Wacker and Antti-Pekka Jauho,*Danmarks Tekniske Univ.*

TuP-67 **Generation of terahertz electromagnetic pulses by electrically heated electrons in two-dimensional semiconductor systems**
W.Xu, C.Zhang and S.M.Stewart, *Univ. of Wollongong*

TuP-68 **Thermoelectric transport properties of Si/SiGe/Si two dimensional hole gases**
I.G.Gerleman, O.A.Mironov, P.J.Phillips, E.H.C.Parker and T.E. Whall
Univ. of Warwick

TuP-69 **Acoustoconductivity of quantum wires**
A.Shik, *A.F.Ioffe PTI*, M. Blencowe, *Imperial College*

TuP-70 **Infrared induced emission from silicon quantum wires**
N.T.Bagraev, E.I.Chaikina, *A.F.Ioffe PTI*
W.Gehlhoff, *Tech. Univ. Berlin*
L.E.Klyachkin, I.I.Markov, *A.F.Ioffe PTI*

TuP-71 **Acoustic phonon modes of free-standing rectangular wires**
N.Nishiguchi, Y.Ando, *Hokkaido Univ.*, M.N.Wybourne, *Univ. of Oregon*

TuP-72 **Highly confined T-shaped quantum wires**
H.Gislason, W.Langbein and J.M.Hvam, *Tech. Univ. of Denmark*

TuP-73 **Fabrication and photoluminescence of AlGaAs/GaAs quantum wire superlattices on V-grooved substrate**
Xue-Lun Wang, Matsuo Ogura, Hirofumi Matsuhata, Tetsuya Tada
Electrontech. Lab. Japan

TuP-74 **Normal-super-normal double tunnel junction fabricated in a split-gate wire**
N.Aoki, T.Kikutani, A.Oki, C.U.Hong, H.Hori and S.Yamada, *JAIST, Japan*

TuP-75 **Near field microscopy of semiconductor waveguides**
C.D.Poweleit, S.M.Lindsay, D.H.Nagaski, J.T.Boyd, H.E.Jackson
Univ. of Cincinnati

TuP-76 **Electro-optic processes in InGaAs/GaAs quantum wires grown on patterned substrates**
R.Rinaldi, M.DeVittorio and R.Cingolani, *Univ. di Lecce*
L.DeCaro, L.Tapfer, *Centro Nazionale Ricerca e Sviluppo Mat., Italy*
U.Marti and F.K.Reinhart, *EPFL Lausanne*

TuP-77 **Nonlinear optical properties of semiconductor quantum wires**
V.Dneprovskii, N.Gushina, *Moscow St. Univ.*
V.Karavanskii, *General Phy. Inst.*, V.Poborchii, I.Salamatina, *Ioffe PTI,*
E.Zlnikov, *Moscow St. Univ.*

TuP-78 **Excitonic non-linear magneto-optical properties of a quantum wire**
A.Balandin and S.Bandyopadhyay, *Univ. of Nebraska*

TuP-79 **Raman scattering from confined phonons in GaAs/AlGaAs quantum wires**
B.H.Bairamov, A.Aydinli, B.Tanatar, F.N.Timofeev, V.Smirnitski, *Bilkent Univ.*,
S.V.Ivanov, B.Y.Mek'tser, *A.F.Ioffe PTI*

TuP-80 **Introducing self-consistency to edge state scattering in quantum dots: experimental implications**
J.P. Bird, M.Stopa, K.Ishibashi, Y.Aoyagi and T.Sugano, *RIKEN, Japan*

TuP-81 **Many-electron ground states in anisotropic parabolic quantum dots**
A.Natori, M.Fujito, Y.Sugimoto and H.Yasunaga, *Univ. of Electro-Comm. Chofu*

TuP-82 **Temperature dependence of relaxation times in electron focusing and antidot structures made from InGaAs/InP heterojunctions**
J.Heremans, *General Motors*, V.Bayot, *UCL Louvain*
B.K.Fuller and C.M.Thrush, *General Motors*

TuP-83 **Single electron charging of the quantum dot: beyond the continuum approximation**
S.Nagaraja, P.Matagne, V.Y.Thean, J.P.Leburton, *Univ. of Illinois*

TuP-84 **Coupled quantum dots as quantum exclusive-OR gate**
José A.Brum and Pawel Hawrylak, *NRC Canada*

TuP-85 **Field dependent phase coherence of trapped electron in gated quantum dot**
Y.Ohkubo, N.Sasaki, Y.Ochiai, *Chiba Univ. Japan*
K.Ishibashi, J.P.Bird, Y.Aoyagi and T.Sugano, *RIKEN, Japan*

TuP-86 **Conditions for the functionality of basic cells for quantum cellular automata**
M.Macucci and G.Iannaccone, *Univ. degli Studi di Pisa*

TuP-87 **Nonlinear low-temperature transport of electrons through a multilevel quantum dot**
T.Inoshita, *Quantum Transition Project, JDRC*
Y.Kuramoto, *Tohoku Univ.*, H.Sakaki, *Univ. of Tokyo*

TuP-88 **Excitons and multi-exciton complexes bound to a 2-D hole layer at a silicon surface: the Kondo effect, the coulomb blockade and a negative photoconductivity**
P.D.Altukhov, E.G.kuzminov and G.V.Ivanov, *A.F.Ioffe PTI*

TuP-89 **Excitonic optical transitions as a probe of self-organized growth of ZeTe(CdTe) islands in (001)-grown CdTe(ZnTe) quantum wells**
V.Calvo, *CNRS - Montpellier II*, Q.X.Zhao, *MPI, Stuttgart*
P.Lefebvre, *CNRS - Montpellier II,*
J. Allègre, A.Bellabchara, H.Mathieu, *CNRS - Montpellier II*
N.Magnea, *C.E.A. Grenoble*

TuP-90 **Quantum confinement effects on the optical phonons of CdTe quantum dots**
A.M. de Paula, L.C.Barbosa, C.H.B.Cruz, O.L.Alves, J.A.Sanjurjo and C.L.Cesar
Univ. Estadual de Campinas, Brazil

TuP-91 **Technological aspects of preparation of semimagnetic semiconductor quantum dots**
S.V.Medynskiy, *State Univ. Chernivtsi, Ukraine*
P.I.Nikitin, *General Phy. Inst. Moscow*
A.I.Savchuk, I.D.Stolyarchuk, *State Univ. Chernivtsi, Ukraine*

TuP-92 **Ground-state energy of an exciton in a quantum-dot superlattice grown on a terraced substrate**
Guy Lamouche, Yves Lépine, *Univ. de Montréal, Quebec*

TuP-93 **Size, position and direction control on GaAs and InAs nano-whisker growth**
T.Shimada, K.Hiruma, M.Shirai, M.Yazawa, K.Haraguchi, M.Matsui and T.Katsuyama,
Hitachi, Japan

TuP-94 **Vertically coupled(In.Ga)As quantum dots in a GaAs matrix**
A.O.Kosogov, P.Werner, *MPI, Stuttgart*
N.N. Ledentsov, V.M.Ustinov, I.V.Kochnev, M.V.Maximov, N.A.Bert, P.S.Kop'ev
A.F.Ioffe PTI
U.Gösele, *MPI, Stuttgart*, D.Bimberg, *Technische Univ. Berlin*

TuP-95 **Simulation of STM images of adatoms on Gallium Arsenide**
Th. Laloyaux, H.Tang and J.P.Vigneron,
Facultés Univ. Notre-Dame de la Paix, Namur

TuP-96 **Nanolithographic patterning of thin metal films with a scanning probe microscope**
S.Melinte, B.Nysten and V.Bayot, *Univ. Catholique de Louvain*

TuP-97 **Detection of optical and electronic properties of low dimensional structures by surface photovoltage spectroscopy**
N.Ashenasy, L.Kronik, *Tel Aviv Univ.*, M.Leibovitch, *CUNY, Brooklyn*
S.Gorer, G.Hodes, *Weizmann Inst. of Sci.*, Y.Rosenwaks, *Tel Aviv Univ.*
M.C.Hanna, *Nat. Renewable Energy Lab.*
Prakhya Ram, *CUNY, Brooklyn*
Yoram Shapira, *Tel Aviv Univ.*

TuP-98 **An investigation of coherent current injection from ohmic spikes in nanostructures**
R.P.Taylor, R.Newbury, *Univ. of New South Wales*
A.S.Sachrajda, Y.Feng, P.T.Coleridge and J.P.McCaffrey, *NRC, Canada*

TuP-99 **Vanishing of the Mott Transition in Semiconductor Nanocrystals**
G.Tamulaitis, S.Jursenas, G.Kurilcik and A.Zukauskas, *Vilnius Univ. Lithuania*

Wednesday, July 17

WeA Symposium on microcavities I

8:30-10:00 chair : **H.C. Lin, NRC Ottawa**

8:30 **Photonic bandgap structures operating at optical wavelengths**
WeA-1 A. Scherer, *Caltech (invited)*
9:00 **Motional narrowing and related optical effects in semiconductor quantum microcavities**
WeA-2 D. Whittakher, *University of Sheffield (invited)*
9:30 **Light emission from excitons in microcavities**
WeA-3 R. Stanley, *EPFL, Lausanne (invited)*

10:00 Coffee break

WeB Symposium on microcavities II

10:30-11:45 chair : **A. Scherer, Caltech**

10:30 **Electron- and photon-manipulation in microcavities and practical applications**
WeB-1 M. Yamanishi, *Hiroshima University (invited)*
11:00 **Exciton-polariton dynamics in a *GaAs* bulk microcavity**
WeB-2 S. Ceccherini, M. Gurioli, F. Bogani, M. Colocci, A Tredicucci, F. Beltram, L. Sorba, *INFM*
11:15 **Two dimensional exciton polaritons in microcavities with embedded quantum wires**
WeB-3 A.V. Kavokin, E.L. Ivchenko, M.A. Kaliteevski, M.R. Vladimirova, *Ioffe Institute*
11:30 **Temperature tuning of exciton-photon coupling in a microcavity grown on a (311)A *GaAs* substrate**
WeB-4 F.M. Matinaga, L.A. Cury, E.C. Valadares, M.V.B. Moreira, W.N. Rodrigues and A.G. de Oliveira *Universidade federal de Minas Gerais*
J.M.C. Vilela, M.S. Andrade and J.A. Sluss, *Fundação centro tecnológico de Minas Gerais CETEC*

12:00 Excursion to Brugge

Thursday, July 18

ThA Low-dimensional structures and quantum wires

8:30-10:30 **chair : Y. Shiraki, JSPS London**

8:30 **Recent progresses in quantum structures**
ThA-1 H. Sakaki *University of Tokyo (invited)*

9:00 **Controlled dislocation slipping : an original method to create multi-quantum-wire structures**
ThA-2 L. Ressier, J.P. Peyrade, F. Voillot, *Laboratoire de physique des solides de Toulouse*
C. Vieu, *L2M-CNRS Bagneux*

9:15 **Uniform *GaAs* quantum wires formed on vicinal *GaAs*(110) surfaces by two-step MBE growth**
ThA-3 M. Takeuchi, T. Takeuchi, Y. Inoue, T. Kato, K. Inoue and H. Nakashima, *Osaka University*
P. Fisher, J. Christen, *Otto-von-Guericke Universität Magdeburg*
M. Grundmann, D. Bimberg, *Technische Universität Berlin*

9:30 **Breakdown of the one-electron picture in low-dimensional electron systems**
ThA-4 T. Mélin and F. Laruelle, *L2M,CNRS, Bagneux*

9:45 **Large excitonic confinement in asymmetric quantum T-wires**
ThA-5 J. Hasen, L.N. Pfeiffer, A. Pinczuk, H.U. Baranger, K.W. West and B.S. Dennis
Bell labs, Lucent technologies

10:00 **Conductance anomalies in strained quantum wires: the case of *PbSe* and *PbTe***
ThA-6 G. Grabecki, J. Wróbel, T. Dietl, M. Sawicki and T. Skośkiewicz, *Polish academy of sciences*
E. Papis, E. Kamińska, A. Piotrowska, *Institute of electron technology, Warszawa*
Y. Ueta, G. Sprinholtz and G. Bauer, *Johannes Kepler Universität Linz*

10:15 **Carrier confinement in self-ordered *AlGaAs* vertical quantum wells**
ThA-7 E. Martinet, A. Gustafsson, G. Biasiol, F. Reinhardt and E. Kapon, *EPFL Lausanne*

10:30 **Exciton diffusion dynamics in quantum nanostructures on V-groove patterned substrates**
ThA-8 N. Usami, *RCAST*
W. Pan, H. Yaguchi, K. Onabe, *University of Tokyo*
Y. Shiraki, *RCAST*

10:45-11:15 Coffee break - papers per title

ThB Coherent transport in quantum structures

11:15-12:30 **chair : M. Helm, Linz University**

11:15 **Phase-controlled currents in semiconductor quantum structures**
ThB-1 P. Cokrum, *NRC, Ottawa (invited)*

11:45 **Antiresonant hopping phenomena in a 1D superlattice**
ThB-2 A. Nogaret, L. Eaves, P.C. Main, T.J. Foster, M. Henini, *University of Notthingham*
G. Hill, *University of Sheffield*

12:00 **Direct ballistic electron spectroscopy of vertical superlattice minibands**
ThB-3 C. Rauch, G. Strasser, K. Unterrainer, W. Boxleitner, E. Gornik, *TU Vienna*
B. Brill, U. Meirav, M. Heiblum, *Weizmann Institute of Science*

12:15 **Microstrip stabilized semiconductor asymmetrical quantum well structure generator for millimeter and submillimeter wavelength range**
ThB-4 A.A. Beloushkin, A.S. Ignatyev, A.L. Karuzskii, V.N. Murzin, A.V. Perestoronin and A.M. Tskhovrebov
P.N. Lebedev physical institute

12:30 Lunch

ThC Terahertz phenomena and Bloch oscillations

14:00-15:15 **chair : R. Evrard, University of Liège**

14:00 **Observation of Shapiro steps and direct Bloch oscillations in semiconductor superlattices**
ThC-1 K. Unterrainer, *University of Vienna (invited)*

14:30 **Transition from classical to quantum dynamics in superlattices in intense THz electrical fields**
ThC-2 S. Zeuner, B.J. Keay, S.J. Allen, K.D. Maranowski, A.C. Gossard, U. Bhattacharya, M.J.W. Rodwell
UC Santa Barbara (invited)

15:00 **THz emission from a narrow-band superlattice - experimental evidence for the shortcomings**
ThC-3 **of the Bloch equation method**
F. Wolter, P. Haring Bolivar, A. Müller, H.G. Roskos, *RWTH Aachen*
K. Köhler, *Fraunhofer-Institut für angewandte festkörperphysik*
H. Kurz, *RWTH Aachen*

15:15-15-45 Coffee break - papers per title

ThP Poster session

15:45-17:45

ThP- 1 **Ground state exciton condensate in a coupled electron-hole system**
Y. Naveh and B. Laikhtman, *The Hebrew Univ.*

ThP- 2 **Spin relaxation of carriers photo-excited in doped semiconductor heterostructures**
M. Z. Maialle and M. H. Degani, *Universidade São Francisco*

ThP- 3 **The inter-island energy transfer and the in-plane exciton migration in AlGaAs/GaAs quantum wells detected by exciton dynamics**
M. Godlewski, *Polish Aca. of Sci.*;
P. O. Holz, J. P. Bergman and B. Monemar, *Linkoping Univ.*;
K. Reginski and M. Bugajski, *Inst. of Electron Tech., Warsaw*;
E. M. Goldys and T. L. Tansley, *Macquarie Univ.*

ThP- 4 **GaAs quantum well islands formed by sub-monolayer AlAs masking and thermal desorption**
T. A. Strand, R. L. Naone, L. A. Coldren, P. M. Petroff and E. L. Hu, *University of California - Santa Barbara*

ThP- 5 **Phase transition in a two-dimensional dipole-oriented exciton system**
T. Fukuzawa, *IBM Res., Tokyo*;
S. Y. Kim, T. K. Gustafson and E. E. Haller, *University of California - Berkeley*;
E. Yamada, *Meisei University*

ThP- 6 **Properties of photoexcited electrons and holes in undoped GaAs/AlGaAs QW's studied by classical cyclotron resonance**
M. Kozhevnikov, B. M. Ashkinadze, E. Cohen, Arza Ron, *Technion*;
L. N. Pfeiffer, *AT&T Bell Labs.*

ThP- 7 **Experimental and theoretical study of the light-hole band-edge configuration in $In_xGa_{1-x}As/GaAs$ multiple quantum wells;**
T. Worren, O. Hunderi, E. Selvig and B. O. Fimland, *Norwegian Univ. of Sci. and Tech.*

ThP- 8 **Up-conversion luminescence via a below-gap state in GaAs/AlgGaAs quantum wells**
N. Kamata, K. Hoshino, T. Uchida and K. Yamada, *Saitama University*;
M. Nishioka and Y. Arakawa, *Univ. of Tokyo*

ThP- 9 **Spin dependent processes in exciton-electron scattering in quantum well structures with a 2DEG**
V. Kochereshko and A. Platonov, *A. F. Ioffe Physico-Technical Inst.*;
F. Bassani and R. T. Cox, *CEA-Grenoble*

ThP-10 **Temperature dependent photoluminescence of Te-doped GaSb/AlSb superlattices**
G. Ru, A. Li and Y. Zheng, *Shangai Inst. of Metallurgy*;
W. Shen, *Shangai Inst. of Technical Phys.*

ThP-11 **Effect of tensile strain on optical properties of AlGaP-based neighboring confinement structure**
T. Ohta, N. Usami, F. Issiki and Y. Shiraki, *Univ. of Tokyo*

ThP-12 **Photoluminescence and photoluminescence excitation of AlGaAs/GaAs single quantum wells with growth interrupted heterointerfaces grown by molecular beam epitaxy**
H. Nakashima, T. Takeuchi and K. Inoue, *Osaka Univ.*;
T. Fukunaga, *Fuji Photo Film Co. Ltd.* ;
D. Bimberg, *Technische Universität Berlin*;
J. Christen, *Universität Magdeburg*

ThP-13 **Luminescence from n- and p-type δ-doping wells in GaAs: a comparative theoretical study**
G.M. Sipahi, R. Enderlein, L.M.R. Scolfaro and J.R. Leite, *Universidade de São Paulo*

ThP-14 **Spatially direct radiative recombinations observed in multiple δ-doped GaAs layers**
A. Levine, E.C.F. da Silva, L.M.R. Scolfaro, D. Beliaev, A.A. Quivy, R. Enderlein, and J.R. Leite
Universidade de São Paulo

ThP-15 **Evidence for metal-insulator transition at B=0 in $Si/Si_{0.87}Ge_{0.13}/Si$ quantum wells**
M. D'Iorio, D. Brown and H. Lafontaine, *National Res. Council of Canada*;
J. Lam, *Univ. of Ottawa* ;
D. Stewart, *Stanford Univ*
S. Deblois, *Université Laval*

ThP-16 **Superlattice vertical transport with high-lying minibands**
X. L. Lei, *Shanghai Inst. of Metallurgy*;
I. C. da Cunha Lima and A. Troper, *UERJ, Brazil*

ThP-17 **Influence of Γ-X mixing on carrier transport and photoluminescence in GaAs/AlAs type-I superlattices**
N. Ohtani, M. Hosoda, H. Minura, K. Tominaga and T. Watanabe,
ATR Optical & Radio Comm. Res. Lab.;
K. Fujiwara , *Kyushu Inst. of Tech.*

ThP-18 **Resonant Γ-X-Γ tunnelling in GaAs/AlAs/GaAs single barrier heterostructures at zero and elevated magnetic field**
J. J. Finley, M. S. Skolnick, J. W. Cockburn, R. Grey, G. Hill and M. A. Pate, *Univ. of Sheffield*;
R. Teissier, *CNRS - Bagneux Cedex*

ThP-19 **Γ to X_z electron transfer times in type-II GaAs/AlAs superlattice due to emission of confined and interface phonons**
G. Weber, *Universidade de São Francisco*;
A. M. de Paula, *Universidade Estadual de Campinas*

ThP-20 **High field transport in superlattices: observation of the Stark-Cyclotron resonance**
L. Canali , F. Beltram, *Scuola Normale Superiore and INFM* ;
M. Lazzarino and L. Sorba, *Laboratorio TASC dell'INFM*

ThP-21 **Investigations of band non-parabolities in strain-balanced GaInAs/GaAlInAs coupled quantum wells**
R. W. Martin and F. McGow, *Strathclyde Univ.*;
M. Hopkinson and J. P. R. David, *Univ. of Sheffield*

ThP-22 **A study of GaInP-GaAs interfaces: metallurgical coupling of successive quantum wells**
O. Schuler, O. Dehaese, X. Wallart and F. Mollot,
Institut d'Electronique et de Microélectronique du Nord.

ThP-23 **Polariton-atom bound state in dispersive medium: application to III-V semiconductors**
M. Singh and V. I. Rupasov, *Univ. of W. Ontario and Landau Inst.*

ThP-24 **Nonequilibrium optical phonon distribution function in double-barrier GaAs/AlAs quantum well**
V. V. Mitin, N. A. Bannov and G. Paulavičius, *Wayne State Univ.*

ThP-25 **Raman study of confinement of optical phonons in GaAs QWWs on facet (311)A GaAs**
V. A. Volodin, M. D. Efremov, V. Ya. Prints, V. V. Preobrazhenskii and B. R. Semyagin,
Inst. of Sem. Phys., Novobirsk

ThP-26 **Infrared induced intrasubband transitions effect on the Raman spectrum of III-V semiconductors**
M. Bendayan and R. Beserman, *Technion-Israel Inst. of Tech.*;
R. Kapon and A. Sa'ar, *The Hebrew Univ. of Jerusalem*;
R. Planel, *CNRS - Bagneux*

ThP-27 **Interface roughness broadening of intersubband transitions**
K. Campman, H. Schmidt, A. Imamoglu and A. Gossard, *Univ. of California - Santa Barbara.*

ThP-28 **Intersubband lifetime in a coupled-quantum well with $\Delta E < \hbar\Omega_{LO}$: time-resolved steady-state measurements**
J. N. Heyman, *Macalester College*;
K. Unterrainer, *Institut für Festkörperelektronik und Mikrostrukturzentrum*;
K. Craig, J. Williams, M. S. Sherwin, K. Campman, P. F. Hopkins and A. C. Gossard,
Univ. of California - Santa Barbara ;
B. N. Murdin and C. J. G. M. Langerak, *FOM-Inst. "Rijnhuizen"*

ThP-29 **Electro-optical phenomena accompanying electron and hole heating in superlattices and quantum wells GaAs/AlGaAs and Ge/GeSi**
L. E. Vorobjev, S. N. Danilov, E. A. Zibik, D. A. Firsov and V. A. Shalygin,
St. Petersburg State Technical Univ.;
A. Ya. Shick and I. I. Saidashev, *Ioffe Physico-Technical Inst.* ;
A. Ya. Aleshkin, O. A. Kuznetsov and L. K. Orlov, *Inst. for Phys. of Microstructures, RAS Novgorod*

ThP-30 **Polarization dependent intersubband absorption and normal-incidence infrared detection in p-type Si/SiGe quantum wells**
P. Kruck, A. Weichselbaum, M. Helm, T. Fromherz and G. Bauer, *Universität Linz*;
J. F. Nützel and G. Abstreiter, *TU München*

ThP-31 **Broad-band microwave detection with a novel 2-D hot-electron device**
S. Barbieri, F. Mango and F. Beltram, *Scuola Normale Superiore*;
M. Lazzarino and L. Sorba, *Superfici e Catalisi Dell'Istituto Nazionale di Fisica della Materia.*

ThP-32 **Electro-absorption modulator using a type II quantum well in the $In_xGa_{1-x}As/InP$ system**
C. Lugand, T. Benyattou and G. Guillot, *INSA-Lyon*;
T. Venet, M. Gendry and G. Hollinger, *Ecole Centrale de Lyon.*

ThP-33 **Photodiffraction in GaInAs/GaInAsP multiquantum wells**
R. Grac, M. Pugnet and J. H. Collet,
CNRS - Toulouse;
B. Lambert, C. De Matos, H. L'Haridon and A. Le Corre, *France Télécom CNET/LAB. - Lannion*

ThP-34 **Electro-optic effects in GaAs/AlGaAs parabolic quantum well structures**
W. Geißelbrecht, A. Masten, O. Gräbner, M. Forkel and G. H. Döhler, *Universität Erlangen-Nürnberg*;
K. Campman and A. C. Gossard, *Univ. of California - Santa Barbara* .

ThP-35 **Photonic crystal made by close packing SiO_2 submicron spheres**
C. López, L. Vázquez, F. Meseguer, R. Mayoral and M. Ocaña
Instituto de Ciencia de Materiales (CSIC), Madrid;
H. Míguez, *Instituto de Tecnología Química (CSIC-UPV), Valencia*

ThP-36 **Photonic Band structures of two-dimensional compound systems: The face centered graphite lattices**
Y. Chen, *CNRS - Bagneux.*

ThP-37 **Investigation of photonic band gaps in a two-dimensional graphite structure made of GaAs**
Y. Chen, G. Faini and H. Launois,
CNRS - Bagneux;
J. Etrillard, *France Telecom, CNET - Bagneux.*

ThP-38 **Optical study of magnetically induced coupling of a quantum well and a semimagnetic semicondictor microcavity**
F. Kany, H. Ulmer-Tuffigo, J. Bleuse, G. Feuillet and J. L. Pautrat, *CEA - Grenoble*;
R. André, *Université Joseph Fourier*

ThP-39 **Time-resolved photoluminescence measurements on strong coupling semiconductor microcavities**
B. Roycroft, J. P. Doran, J. O'Gorman and J. Hegarty, *Trinity College*;
R. P. Stanley, R. Houdre, U. Oesterle and M. Ilegems, *EPFL Lausanne.*

ThP-40 **Size quantization of acoustic phonons in microcrystals embedded in a glass matrix**
N. Ovsyuk and V. Novikov
Institute of Mineralogy and Petrology, Novobirsk;

ThP-41 **II-VI weak coupling microcavity structures**
T. Aherne, J. P. Doran and J. Hegarty, *Trinity College*;
A. Salokatve, P. Uusimaa, K. Rakennus and M. Pessa, *Tampere Univ. of Tech.*

ThP-42 **Strong coupling regime in pillar semiconductor microcavities**
J. Bloch, *CNRS Bagneux*
J.M. Gérard, D. Barrier, J.Y. Marzin, *France Télécom*
R. Planel, V. Thierry-Mieg, *CNRS Bagneux*
E. Costard, *Thomson-CSF/LCR*

ThP-43 **Study of photonic band structure of 3D ordered silica matrices**
V. N. Astratov, V. N. Bogomolov, A. A. Kaplyanskii, O. Z. Karimov, A. V. Prokofiev and Yu. A. Vlasov, *A. F. Ioffe PTI.*

ThP-44 **Strain effect on the excitation threshold of HgCdZnTe heterostructure lasers in the 3-5 μm waveband**
J. Bonnet-Gamard, J. Bleuse, G. Mula and N. Magnea, *CEA*

ThP-45 **Time dependent exciton spectroscopy in $Zn_{1-x}Cd_xSe/ZnSe$ multiple quantum well lasers**
D. Greco, L. Calcagnile and R. Cingolani, *Università di Lecce*;
M. Lomascolo and M. Di Dio, *PASTIS-CNRSM - Brindisi*;
L. Vanzetti, L. Sorba and A. Franciosi, *Laboratorio Nazionalle Tecnologie Avanzate Superfici e Catalisi dell'Istito Nazionale per las Fisica della Materia.*

ThP-46 **Spatial expansion of exciton magnetic polarons in $Zn_{1-x}Mn_xSe/ZnSe$ multiple quantum wells**
G. A. Balchin, C. D. Poweleit and L. M. Smith, *Univ. of Cincinnati*;
B. T. Jonker, *Naval Res. Lab., Washington*

ThP-47 **Interference effects in electrical resistivity and spin valve magnetoresistance in magnetic layered structures**
J. Barnaś and Y. Bruynseraede, *K. U. Leuven.*

ThP-48 **Raman scattering from a magnetically modulated 2DEG subject to a normal magnetic field**
V. Fessatidiss, *Fordham University*
H.L. Cui, *Stevens Institute of Technology*
P. Vasilopoulos, *Concordia University*

ThP-49 **Gate voltage induced realization of different rational fractions of h/e^2 at fixed values of current and magnetic field**
M. Blöcker, F. J. Ahlers and L. Bliek, *Physikalisch-Technische Bundesanstalt*;
G. Nachtwei, *Max-Planck-Institut für Festkörperforschung.*

ThP-50 **Circular inhomogenous magnetic field profiles in electron waveguide junctions**
X. Q. Li and F. M. Peeters, *Univ. of Antwerp (UIA).*

ThP-51 **Inductive probing of the integer quantum hall effect**
E. Yahel and A. Palevski, *Tel Aviv Univ.*;
D. Orgad and H. Shtrikman, *The Weizmann Inst. of Sci.*

ThP-52 **Quasiparticle lifetime τ_{ee} of electron-electron interactions for 2D electron gases with magnetic field**
S. Xu and X. C. Xie, *Oklahoma State Univ.*;
T. Kawamura, *State Univ. of New York - Stony Brook*;
B. Y. K. Hu, *Danmarks Tekniske Univ.*

ThP-53 **Strong dependence of the multichannel ballistic transport on the geometrical symmetry**
M. Shin, K. W. Park, S. Lee and E. H. Lee, *Electronics and Telecommunications Res. Inst. - Taejon*

ThP-54 **Forcing of chaos in semiconductor superlattices**
L. L. Bonilla and O. M. Bulashenko, *Universidad Carlos III de Madrid*

ThP-55 **DX-center and pressure effects on electronic structure of a δ-doped quantum barrier**
J. M. Shi, F. M. Peeters and J. T. Devreese, *Universiteit Antwerpen (UIA)*;
P. M. Koenraad, A. F. W. van der Stadt and J. H. Wolter, *Technische Universiteit Eindhoven*

ThP-56 **Magnetic-field-induced reduction of singlet binding energies of Off-well-center negative donor ions in GaAs/AlGaAs multiple quantum wells**
Z. X. Jiang, B. D. McCombe and J. L. Zhu, *SUNY at Buffalo*;
W. Schaff, *Cornell Univ.*

ThP-57 **Accumulation layer and interface effects in doped nonabrupt $GaAs/Al_xGa_{1-x}As$ single quantum wells**
A. K. Freire, F. A. Farias and V. N. Freire, *Univerdidade Federal do Ceará*;
E. C. Ferreira, *Universidade Federal do Rio Grande do Norte*

ThP-58 **Interface roughness: a reason for inaccessibility of the negative resistance region in resonant-tunnelling devices**
T. Figielski, T. Wosiński and A. Mąkosa, *Polish Academy of Sciences*

ThP-59 **Semiconductor lasers controlled by electron extraction via resonant-tunneling structure**
V. Ryzhii, I. Khmyrova and M. Ryzhii, *Univ. of Aizu*

ThP-60 **Tuning the inter-subband tunnelling and UCF with an in-plane magnetic field in the 'quantum transport regime'**
M. J. Gompertz, T. Inh, A. Nogaret, P. C. Main, L. Eaves and M. Henini, *Univ. of Nottingham*;
S. P. Beaumont, *Univ. of Glasgow*

ThP-61 **Study of random telegraph signals in GaAs/AlGaAs single-electron transistor**
T. Sakamoto and K. Nakamura, *NEC Fundamental Res. Lab.*

ThP-62 **Nonlinear operation of finite-size tunnel junction between 2D electron systems**
O. E. Raichev and F. T. Vasko, *Inst. of Semiconductor Phys., Kiev*

ThP-63 **Coherent bloch-phonon oscillations in semiconductor superlattices**
T. Dekorsy, G. C. Cho, A. M. T. Kim and H. Kurz, *Institut für Halbleitertechnik*;
K. Köhler, *Fraunhoferinstitut für Angewandte Feskörperphysik*

ThP-64 **Dynamical localization and stimulated absorption and emission induced by a THz field in a double quantum well**
R. Aguado and G. Platero, *Instituto de Ciencia de Materiales (CSIC)*

ThP-65 **Franz-Keldysh oscillations at the miniband edge in a $GaAs/Al_xGa_{1-x}As$ superlattice**
M. Ando, M. Nakayama and H. Nishimura, *Osaka City Univ.*;
H. Schneider, *Fraunhoferinstitut für Angewandte Fesköperphysik*;
K. Fujiwara, *Kyushu Inst. of Tech.*

ThP-66 **Theoretical studies of subband carrier lifetimes in an optically pumped 3-level asymmetric quantum well terahertz laser**
P. Harrison and R. W. Kelsall, *Univ. of Leeds*

ThP-67 **Dynamics of strongly driven two-level systems: analytical solutions**
M. Wagner, *Hitachi Cambridge Lab.*;
P. Vasilopoulos, *Concordia Univ.*

ThP-68 **Theory of electron transport in a THz-field irradiated semiconductor superlattice: occurence of quantized DC voltages and current responsivity**
A. A. Ignatov, E. Schomburg, J. Grenzer, S. Winnerl and K. F. Renk, *Universität Regensburg*;
E. P. Dodin, *Inst. of Phys. of Microstructures, RAS*

ThP-69 **Intersubband lasing in Silicon-bsed quantum well structures**
L. Friedman and R. A. Soref, *Univ. of Massachusetts - Boston*

ThP-70 **Functional properties of luminescent porous silicon as a component of optoelectronic integration**
M. Araki, T. Ozaki, X. Sheng, H. Koyama and N. Koshida, *Tokyo Univ. of Agri. and Tech.*

ThP-71 **Ballistic transport in quantum cylinders**
A. V. Chaplik, D. A. Romanov and L. I. Magarill, *Inst. of Semiconductor Phys., Novosibirsk*

ThP-72 **Conditions for direct band-gap in Si wires**
S. Horiguchi, *NTT LSI Lab.*

ThP-73 **Quantum tunnel reflectors and superlattices on their basis**
Z. S. Gribnikov, A. N. Korshak and N. Z. Vagidov, *Ukranian Nat. Academy of Sci.*

ThP-74 **The optical absorption of quantum-well wires**
S. Glutsch and F. Bechstedt, *Friedrich-Schiller-Universität Jena*;
D. S. Chemla, *Univ. of California - Berkeley*

ThP-75 **Optical properties of the semiconductor and metal quantum wires in the chrysotile asbestos nanochannels**
V. V. Poborchii, *Ioffe Physico-Technical Inst.*

ThP-76 **Magneto oscillations in a trapezoidal two-dimensional electron gas grown over GaAs wires**
G. M. Gusev, N. La Scala Jr., D. I. Lubyshev, P. P. González-Borrero, M. A. P. da Silva and P. Basmaji, *Universidade de São Paulo*;
J. C. Rossi, *Universidade Federal de São Carlos*;
J. C. Portal, *CNRS - Grenoble and INSA - Toulouse*

ThP-77 **Electron-phonon phenomena in cylindrical and planar quantum wires**
E. P. Pokatilov, S. N. Klimin, S. N. Balaban and L. C. Fai, *State Univ. at Moldova*
V. M. Fomin and J. T. Devreese, *Universiteit Antwerpen*

ThP-78 **Transport characterization of quantum wires by magnetophonon and magnetic depopulation experiments**
G. Ploner, M. Hauser, J. Smoliner, G. Strasser and E. Gornik, *Mikrostrukturzentrum der TU Wien*

ThP-79 **Folded and confined one-dimensional plasmons in modulated wires**
F. Perez, B. Jusserand, C. Dahl and M. Filoche, *France Télécom CNET*;
L. Ferlazzo-Manin and B. Etienne, *CNRS - Bagneux*

ThP-80 **Self-adjusting formation of a lateral confinement potential in heterostructures with compensating *pn* layers**
U. Wieser, S. Skaberna and U. Kunze, *Ruhr-Universität Bochum*

ThP-81 **Characterization of electron and hole energy levels in self-organized InAs/GaAs quantum dots**
P. Brounkov, N.N. Faleev, Yi. G. Musikhin, A. A. Suvorova, S. G. Konnikov, A. F. Tsatsul'nikov, A. Yu. Egorov, A. E. Zhukov, V. M. Ustinov, N. N. Ledentsov, P. S. Kop'ev and Zh. I. Alferov, *A. F. Ioffe Physico-Technical Inst.*;
D. Bimberg, *Technische Universität Berlin*

ThP-82 **Inelastic light scattering from electronic excitations of quantum dots in a magnetic field**
P. Hawrylak and D. J. Lockwood, *Nat. Res. Council, Ottawa*;
P. D. Wang, *Notre Dame Univ.*;
C. M. Sotomayer Torres, *Glasgow Univ.*;
B. S. Dennis, *AT&T Bell Lab.*

ThP-83 **Time resolved photoluminescence studies of GaAs/AlGaAs quantum dots**
N. Sai, B. Z. Zheng, X. P. Yang, W. Zhang, J. Z. Xu and Z. Y. Xu, *Chinese Acad. of Sci.*

ThP-84 **Resonant tunneling through a semiconductor quantum dot**
K. Natori and N. Sano, *Univ. of Tsukuba*

ThP-85 **Enhancement of luminescence from Te isoelectronic centers in ZnSTe/ZnS quantum dots**
A. Ng, I. K. Sou and W. K. Ge, *Hong Kong Univ. of Sci. and Tech.*;
Y. S. Tang and C. M. Sotomayer Torres, *Glasgow Univ.*;
Z. L. Yuan and Z. Y. Xu, *Nations Superlattice Lab.*

ThP-86 **Commensurability oscillations by runaway and pinned electrons**
K. Tsuagoshi, T. Nagao, M. Haraguchi, S. Takaoka, K. Murase and K. Gamo, *Osaka Univ.*

ThP-87 **Two-Dimensional clusters in SiGe/Si superlattices and their effect on field effect transistor transport characteristics**
D. Girginoudi and A. Thanailakis, *Democritus Univ. of Thrace*;
A. Christou, *Univ. of Maryland - College Park*

ThP-88 **Low temperature transport regime in 3-dimensional lattice of quantum dots**
S. G. Romanov, A. V. Fokin and D. V. Shamshur, *A. F. Ioffe Physico-Technical Inst.*;
D. K. Maude and J. C. Portal, *MPR-CNRS - Grenoble and INSA - Toulouse*

ThP-89 **Size quantization patterns in self-assembled InAs/GaAs quantum dots**
F. Bogani, L. Carraresi, R. Mattolini and M. Colocci, *INFM and LENS - Firenze*;
A. Bosacchi, S. Franchi and P. Frigeri, *CNR-MASPEC - Parma*;
S. Taddei, *Universitá di Firenze*

ThP-90 **Intrinsic and extrinsic photo- and electro-luminescence in Si nanostructures**
L. Tsybeskov, K. D. Hirschman, S. P. Duttagupta, K. L. Moore, D. G. Hall and P. M. Fauchet, *Univ. of Rochester*

ThP-91 **Optical properties of vertically aligned self-assembled InGaAs quantum dots layers on (311)A/B and (100)GaAs substrates**
P.P. González-Borrero, D. I. Lubyshev, E. Marega Jr. and P. Basmaji, *Universidade de São Paulo*

ThP-92 **LO-phonon assisted relaxation of hot electrons in CdZnSe/ZnSe quantum wells and quantum dots**
R. Spiegel, G. Bacher and A. Forchel, *Technische Physik, Universität Würzburg*;
B. Jobst, D. Hommel and G. Landwehr, *Experimentelle Physik III, Universität Würzburg*

ThP-93 **Flux confinement by regular arrays and clusters of antidots in Pb/Cu bilayers**
E. Rosseel, T. Puig, M. J. Van Bael, M. Baert, V. V. Moshchalkov and Y. Bruynseraede, *Katholieke Universiteit Leuven*;
R. Jonckheere, *Interuniversity Micro-Electronics Center, Leuven*

ThP-94 **Microstructuring of Si(100) with light-induced dry etching in the VUV**
U. Streller, A. Krabbe and N. Schwentner, *FU Berlin*

ThP-95 **Single-electron tunneling in granular Ag-SiO_2 films**
M. Fujii, T. Kita, S. Hayashi and K. Yamamoto, *Kobe Univ.*

ThP-96 **Scanning tunnel microscopy of fullerene monolayers**
V. A. Fedirko, *Moscow State Univ. of Tech. "Stankin"*
V. A. Bykov, M. D. Eremchenko, *Research Institute of Physical Problems, Zelenograd*

18:30 Banquet

Friday, July 19

FrA Spectroscopy of silicon nanostructures

8:30-10:15 **chair : U. Kunze, Ruhr-Universität Bochum**

8:30 **STM manipulation of fullerene molecules on *Si* surfaces**
FrA-1 P. Beton *University of Notthingham (invited)*
9:00 **Dynamical STM studies of the growth of *Ge* on silicon by MBE**
FrA-2 M. Kästner, A. Zinner and B. Voigtländer, *Institut für Grenzflächenforschung und Vakuumphysik (invited)*
9:30 ***SiO*$_2$ and *Si* nanoscale patterning with an atomic force microscope**
FrA-3 B. Klehn and U. Kunze, *Ruhr-Universität Bochum*
9:45 **On the origin of blue light emission from *Ge*-nanocrystals containing $a - SiO_x$ films**
FrA-4 R. Weigand, M. Zacharias, J. Bläsing, P. Viet and J. Christen, *Otto-von-Guericke Universität Magdeburg*
10:00 **Visible luminescence in Si/SiO_2 superlattices**
FrA-5 D.J. Lockwood, B.T. Sullivan, P.D. Grant, A. Blais, Z.H. Lu, J-M. Baribeau, H.J. Labbé and J. Stapledon *National Research Council, Ottawa*

10:15 Coffee break

FrB Quantum devices

10:45-11:45 **chair : M. Kelly, University of Surrey**

10:45 **Digital single electronics : Progress and problems**
FrB-1 A. Korotkov, *Stonybrook and Moscow St. U. (invited)*
11:15 **High temperature single-hole silicon transistors**
FrB-2 N.T. Bagraev, *Ioffe Institute*
W. Gehlhoff, *Technische Universität Berlin*
L.E. Klyachkin, A. M. Malyarenko, *Ioffe Institute*
11:30 **Distinct two-dimensional carrier injection phenomena in extremely thin SOI insulated-gate**
FrB-3 **pn-junction devices: Prospect of new device applications**
Y. Omura, *NTT LSI Laboratories, Atsugi*
11:45 **One-dimensional and two-dimensional phenomena in SOI mosfets devices**
FrB-4 X. Baie, J-P. Colinge, V. Bayot, E. Grivei, *Université Catholique de Louvain*

Closing Remark

12:00 **chair : G. Döhler, University Erlangen**

Monday

MoA Superconductor - semiconductor contacts

Induced Superconductivity in InAs Quantum Wells with Superconducting Contacts.

Herbert Kroemer

Department of Electrical and Computer Engineering
and Department of Materials
University of California Santa Barbara, CA 93106

Abstract

Modulation-doped InAs quantum wells with AlSb barriers and superconducting Nb electrodes form a model system for semiconductor-coupled superconducting weak links in the ballistic ("clean") limit. A tutorial outline of their general physics is presented, followed by a discussion of selected properties of monolithic series arrays of such links, especially the puzzling temperature dependence of their current-voltage characteristics.

Low-Dimensional Electron Transport Properties in InAs/AlGaSb Mesoscopic Structures

M. Inoue, T. Sugihara, T. Maemoto, S. Sasa , H. Dobashi, and S. Izumiya
Departmentof ElectricalEngineering, Osaka Institute of Technology,
5-16-1 Ohmiya, Asahi-ku, Osaka 535, Japan

InAs based heterostructures have recently attracted much attention because of their superior transport properties over GaAs or InGaAs based heterostructures, which arise from the lower electron effective mass of InAs and from the strong electron confinement. In an InAs/AlGaSb split-gate device,we have observed quantum effects at higher temperatures around 77K[1]. We have also demonstrated that one-dimensional subband structures are formed for up to 0.4-μm-wide wires by magnetoresistance measurements[2]. These widths are readily attainable using conventional fabrication technique. Therefore, InAs based heterostructures are very promising for the realization of quantum devices operating at higher temperatures. The purpose of this paper is to present the fabrication and characterization of InAs-based mesoscopic structures, such as quantum wires and weak link superconducting devices.

We have fabricated single and multiple QWRs and quantum wire transistors using InAs/AlGaSb single quantum well heterostructures which were grown on semi-insulating GaAs substrates by molecular beam epitaxy. The two-dimensional electron gas (2DEG) mobility was 4 x 10^5 cm^2/Vs at 4.2K. This high quality 2DEG allows us to study the transport properties under quasi-ballistic regime at a wire length of about a few μm. The nonlinear current-voltage characteristics have been observed at 4.2 and 77K. We compare and analyze the results measured on various samples with the wire lengths ranging from 1 to 10 μm.

We have also succeeded to observe modulation of differential conductance by applying gate voltages in an InAs/Pb-In superconducting weak link device. We believe that the observed conductance modulation is a strong evidence of the formation of the superconducting weak link between the source and the drain contacts. The detailed nonlinear transport properties in InAs-based mesoscopic devices are discussed.

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2) S. Sasa, T. Sugihara, K. Tada, S. Izumiya, Y. Yamamoto, and M. Inoue, 3rd Int. Symp. on NPMS, Maui, (1995).

papers per title

Spatial Localization of Energy in Dielectric-Semiconducting Lattices

Alexei A. Bulgakov† and Sergei A. Bulgakov*
† *Institute of Radiophysics and Electronics, Kharkov, Ukraine*
* *Instituto de Ciencia de Materiales, CSIC, Madrid, Spain.*
Permanent address: Radioastronomy Institute, Kharkov, Ukraine

It is known that surface polaritons propagate through the boundary between dielectric and material having dielectric permittivity depending on frequency ($\varepsilon = \varepsilon(\omega)$. Two continuous pass bands appear in the structure built from these slabs. In a such structure we have found new type of polariton, the complex polaritons, the complex polaritons. Properties of such polaritons appear to be very unusual and , to our opinion, their detailed investigation is of significant interest for creating of new types of infrared and optical devices.

Particularities of such complex waves are that their wavenumbers appear to be complex even for lossless medium. This complexity leads to the field increasing at the infinity. From the first opinion such type of solution must be omitted because it seems to have no physical sense. However such complex roots of a wave equation appear to be complex conjugate. Energy flux of a such wave is closed, so that the energy is localized inside certain volume. Therefore, there is no fields divergence at the infinity. In literature such waves are called *complex waves* [1-2].

We have shown that complex waves exist in superlattice pass bands which are associated with polaritons propagation along the boundary of the structure. In contrast with previous knowledge, the imagine part of the wavevector may be a large enough. This leads to energy concentration inside superlattice. Energy circulates along closed orbits localized in the energy contour. Thus, such waves remind particles of energy.

Preliminary investigations show that the interaction between different complex modes is possible even in linear approximation. These occurs because complex waves are not orthogonal function. Such particularity may lead to energy concentration in the highest complex modes.

The next important question in the complex wave study is to take into account dissipating processes. Loses in media may lead to the breaking of the energy contour and energy will be irradiated out from given spatial volume. However, the imagine part of the complex wavevector is much greater than submission of loses. Therefore, dissipation cannot destroy the energy particle but leads to weak energy irradiation out from the circuit. As result, the energy particle may "survive" for a long time.

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PHONON-ASSISTED TUNNELING IN THE HIGH VOLTAGE ELECTRON TRANSPORT IN THE OPAL-BASED 3D MESOSCOPIC CLUSTER LATTICE

V.N. Bogomolov . S.A. Ktitorov. D.A. Kurdyukov. A.V. Prokofiev.
S.M. Samoilovich*. L.M. Sorokin
A.F. Ioffe Physical and Technical Institute. RAS. Politechnicheskaya Str. 26.
Saint-Petersburg,194021. Russia
* Moscow State University,117234. Moscow. Russia

Electron transport in 3D cluster lattices possesses by peculiarities which make them extremely attractive for a study. In particular. in opposite to conventional crystals where electron tunneling between cells formes energy bands. in mesoscopic scale cluster lattices weak tunneling is accompanied by phonon emission processes resulting in new phenomena. Three-dimensional artificial crystals on the base of opal with semiconductor mesoscopic clusters are prepared. Electron microscopy showes a regular array of semiconductor clusters of 800 Å in diameter connected by constrictions. Thermal treating can form ruptures in the middle of these links. Electrons have to tunnel through these constrictions and ruptures in order to move from one cluster to another. Measured current-voltage characteristic (CVC) have a piece-wise linear form with increasing slope: at higher voltages CVC turnes to the $\mathbf{u}^{3/2}$ law. That is not a manifestation of the Child law characteristic for a vacuum diod but is a result of spherical geometry of clusters in the space-charge limited current regime. The abrupt jumps of the slope can be traced back to the threshold peculiarities due to phonon-assisted tunneling. We conclude that phonons involved in these processes are surface ones which are a mixture of longitudinal and transversal modes characteristic of the SiO_2 opal matrix.

Charge density wave in a layered semiconductor structure

V.V.Tugushev, E.A.Zhukovsky

Russian Reseach Center "Kurchatov Institute", 123182 , Moscow, Russia

We describe a charge ordered state of the charge-density wave (CDW) type in a structure formed by III-V semiconductor compounds. These compounds taken alone have no effects of CDW type. However, a synthesis of periodic structures with layers including quantum wells with given parameters allow to obtain such a band scheme of the structure that makes this effect possible. This possibility results from a creation of nanostructures with a given number of size-quantized levels in quantum wells and with their controllable mutual arrangement. The band scheme of the structure is assumed to possess two highly anisotropic close bands. The lower one is thought to be much narrower then the upper in the direction of the structure growth axis. The interaction of electrons from these two bands is allowed for. It is shown that at T=0, on a certain region of parameters an inhomogeneous charge distribution over the layers is more favorable in energy than homogeneous one. A variational ansatz of the charge density wave type is used in the calculation. The self-consistency equations for its parameters are derived and solved at T=0. The phase diagram of the system is obtained.

We point out some experimental possibilities connected with Wannier-Stark ladder and Weiss oscillations to make clear the appearence of a new inhomogeneous charge ordered state. The results of neutronography, X-ray method and optical measurements in GaAs/AlGaAs structures are also analyzed.

SUPERLATTICE FORMATION CAUSED BY THE AUTOOSCILLATIONS DURING DIRECTIONAL SOLIDIFICATION

V.V.Gafiychuk, A.V.Demchuk, I.A.Lubashevskii, A.G.Cadjan

Institute of Applied Problem in Mechanics and Mathematics Nationals Ukrainian Academy of Sciences, 3 b, Naukova str., Lviv, 290603, Ukraine,

e-mail: gaf@viva.lviv.ua

Within the framework of the frozen temperature approximation we develop a strongly-nonlinear theory of one-dimensional pattern formation during directional solidification of binary mixture. When crystals grow layer-by-layer, with their surface being practically parallel to one of the singular faces, the solute segregation to the solid involves two stages: surface trapping of solute atoms by the moving steps and their following incorporation into the crystal bulk. In this case the former process becomes essentially non-equilibrium at slow rates of crystallization typically used in technological processes, viz., at $V \sim 10^{-3}$–10^{-2} cm/sec, causing the total partition coefficient $k(v)$ to depend on the interface velocity v.

In the case of small partition coefficient the full problem is reduced to the system of two ordinary differential equations describing the interface motion in terms of its velocity and position coordinate. The type of the oscillatory instability bifurcation is studied in detail in different limits. For the subcrytical bifurcaton relaxation interface oscillations are analyzed analytically and numerically. We show that these oscillation exibit a number of anomalous properies. In particular, such oscillations can be weakly- or strongly-dissipative depending on the physical parameters and the amplitude of the strongly-dissipative oscillations is determined not only by the form of the corresponding nullcline but also by the behavior of the system for small values of the interface velocity. Characteristic parameters of the superlattice occuring in the growing crystal are estimated for crystallization of InSb with impurities Se and Te and for Si with Al and P.

EFFECTS OF RESONANT TUNNELING ON THE I-V CHARACTERISTIC OF LANGMUIR-BLODGETT-FILM BASED HETEROSTRUCTURES

Alexander I. Onipko
Bogolyubov Institute for Theoretical Physics, Kiev, 252143, Ukraine

We developed the 3D model of resonant tunneling through Langmuir-Blodgett (LB) malty-layer structures connected with metal electrodes, to examine the role of intermolecular electron-transfer parameters in determining the I–V characteristic of metal-LB-film-metal heterostrutures. It is shown that with a reasonable choice of parameters theoretical curve perfectly fits the step-like structure discovered recently in the through-LB-film-current dependence on the applied voltage. It is also shown that this kind of the current-versus-voltage dependence is an inherent feature of the LB film based heterojunctions, where the electron transfer from metal to the LB film with narrow conduction bands is weak. This suggests an explanation of the step-like current structure observed in terms of linear resonant tunneling. We propose the key experimental test for verification of our conclusions.

INSIGHT ON POROUS SILICON LUMINESCENCE MECHANISM FROM GAMMA-IRRADIATION EXPERIMENTS

E.V.Astrova, V.V.Emtsev, A.A.Lebedev, D.S.Poloskin, A.D.Remenyuk, Yu.V.Rud', R.F.Vitman

Physical Technical Institute, Polytekhnicheskaya 26, St.Petersburg, 194021, Russia, e-mail:astrova@silicon.ioffe.rssi.ru

Porous silicon (PS) was formed on p-type silicon, previously subjected to a high dose (10^20 /sq.cm) of gamma-irradiation. The spectrum and intensity of photoluminescece (PL) of such layers were identical to those, formed on nonirradiated substrates. When PS itself was subjected to gamma-irradiation, the PL intensity decreased by 50 times with no shift of the maximum position. The kinetics of the PL degradation obeys an exponential law.

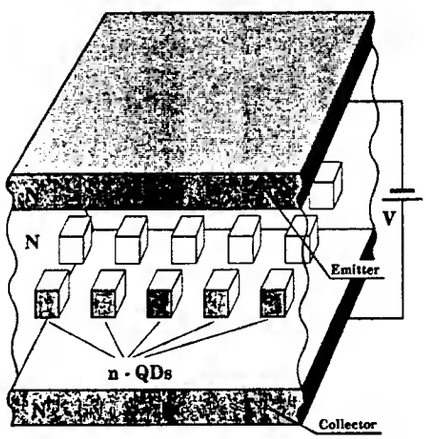
In a quantum confinement model the radiation-induced defects in PS nanocrystals should enhance nonradiative recombination process. These centers were introduced in the irradiated substrate and according to the existing knowledge, must remain in the nanorystals during the etching process, while preparing PS. In spite of the fact, that the lifetime of free carriers in the substrate is drasticaly reduced, the PL properties were found to be unchanged. Moreover, this mechanism should give a reciprocal dose dependence of PL intensity variations, which has been not observed experimentally.

So, the obtained data show, that the most reasonable mechanism of PL degradation is suppresion of light-emitting centers under irradiation.

INFRARED PHOTOTRANSISTORS WITH A TWO-DIMENSIONAL QUANTUM–DOT ARRAY AS A BASE

I. Khmyrova, M. Ryzhii, M. Ershov and V. Ryzhii
Computer Solid State Physics Laboratory, University of Aizu
Aizu-Wakamatsu City, 965-80, Japan

Infrared phototransistors utilizing electron photoexcitation from the bound states in a two-dimensional quantum dot (QD) array are considered. The infrared phototransistor under consideration is formed of a monopolar $N^+ - N - N^+$ structure with a two-dimensional QD array buried in the wide gap N layer (see figure). We suppose that the QD array consists of small n-regions of narrow gap semiconductor. The electron current from one N^+ layer to another under applied voltage is limited by the potential barrier arising due to an electron charge trapped in the QD array. The potential barrier height and in turn the electron current depend on the applied voltage and the intensity of infrared radiation. Lateral nonuniformity of the barrier strongly affects the current. To evaluate the current-voltage characteristictics of the diode structures in question the developed theoretical model is used. It is supposed that each QD has a single quantum level. The electron current is assumed to be of thermionic origin. The electron charge of the QD array is determined by the balance of the electrons exciting from the QDs and capturing in them. Two limiting cases are investigated: weakly coupled QDs, when the QD array forms a lateral two-dimensional superlattice, and uncoupled QDs filled (fully or partially) by localized electrons. In the first case the potential barrier can be considered as approximately uniform in lateral directions. The analytical expression for the current-voltage characteristic is obtained for this case. If the QDs are uncoupled the current density under low voltages is significantly nonuniform in the QD array plane and the current is mainly determined by the areas with the QDs unfilled by the electrons. This is due to low average occupancy of QDs and random distribution of localized electrons in the QD array. The effect of the base potential nonuniformity is evaluated. It is shown that the current is distinctly affected by this effect especially at relatively low voltages.



KINETIC PHENOMENA IN 1D SEMICONDUCTOR SUPERLATTICES

Fridrikh G. Bass[1], Yuriy O. Averkov[2] and Oleg M. Yevtushenko[2]

[1] Bar-Ilan University, Israel;

[2] Institute of Radiophysics & Electronics, Ukrainian Nat. Academy of Sciences,
fax: (0572) 44-11-05; e-mail: yevtushenko@ire.kharkov.ua

This report addresses to study of the Boltsman kinetic equation and transport phenomena in 1D quantum semiconductor superlattices (SL) [1]. Collision integral has a general form [2]. We present *new method of approximate solution of the kinetic equation*. The method is based on the framework analogous to the one presented in Ref. [2]. We explore the simplest case when carriers scatter on the phonons only. Our new method allows to calculate the characteristic relaxation frequencies for SL starting from the microscopic equations. Performing the Fourier transformation with respect to the carrier momentum we obtain the equations for the Fourier components of the distribution function. We suppose the phonons' dispersion being small and develop the perturbation scheme with respect to this small dispersion. The first iteration of the scheme coincides with approximation of the momentum–independent collision frequency (τ–approximation [1]). At the second iteration we *go over the τ–approximation* and derive additional terms that allow to *take into account more correctly real mechanisms of scattering*. In the last part of the work we calculate DC current in SL media and compare our results with the analogous values derived under the τ–approximation [3] and obtained experimentally [4]. The perturbation scheme presented correctly takes into account real mechanisms of scattering. Therefore *the method can be applied as for the uniform problems as for the inhomogeneous cases*. It includes τ–approximation and the Bhatnagar–Gross–Krook model as a specific case and *produces better results for more wide range of the external fields' parameters*.

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MOTION OF THE CONDUCTION ELECTRONS IN CARBON NANOTUBULE UNDER THE ACTION OF AC ELECTRIC AND DC MAGNETIC FIELDS

Dmitriy Romanov[1] and Oleg M. Yevtushenko[2]

[1] Institute of Semiconductor Physics, Russian Academy of Sciences;

[2] Institute of Radiophysics & Electronics, Ukrainian National Academy of Sciences

fax: (0572) 44-11-05; e-mail: yevtushenko@ire.kharkov.ua

Recently properties of carbon nano–structures (fullerenes) have been of great and ongoing interest [1,2]. The fullerenes have various crystal modifications depending on the conditions of preparation [1]. The *object of our study is a carbon nanotubule* (NT) [2]. Such nanotubules are fullerenes that have atoms situated along the helical line wrapped on the surface of cylinder with diameter of the order of (20-100) Å. Having spiral symmetry, NT possesses unusual electron properties [2]. For example, constant magnetic field affects the dispersion relation of the conduction electrons. Changing probability of the electrons' jump along the helical line, it alters an average velocity of the electron motion. In this work we *study combined influence of electric* $E = E_{DC} + E_{AC}\, e^{i\omega t}$ and *magnetic* $H = H_{DC}$ fields on the NT electron properties. External fields are supposed to be parallel to the structure axis. It is well known, that AC electric field applied along the linear chain of atoms crucially changes probability of the electrons' jump from one site to another: AC electric field can turn motion of the carriers from the infinite regime up to localization of the particles [3]. In the case of fullerene media AC electric field affects both possible types of the electrons' jump (along a coil and along the axis of spiral, respectively). Basing on the results presented in the Ref.'s [2] and [3] we prove that *using AC electric field and DC magnetic field we can substantially control electrons' motion in the structure and it's DC conductivity*. Varying parameters of the external fields we can transfer the sample from the high–conducting to the near–dielectric states. Using the Wannier representation in the framework of quantum mechanics we explore in details *how we can control the electron properties of one carbon nanotubule*.

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STIMULATED EMISSION OF FAR-INFRARED RADIATION FROM TWO-DIMENSIONAL PLASMONS IN A PERIODIC SEMICONDUCTOR-METAL MICROSTRUCTURE

O. R. Matov, O. F. Meshkov, O. V. Polischuk, V. V. Popov

Russian Academy of Sciences
Institute of RadioEngineering & Electronics, Saratov Branch
410019 Saratov, Russia

Spontaneous electromagnetic (EM) emission from thermally excited two-dimensional (2D) plasmons in a semiconductor heterostructure with metal grating has been studied both theoretically and experimentally in [1,2]. When plasma waves are already excited, the periodic metal grating acts as an open microresonator and transforms the energy of plasma waves with wave vectors $k = 2\pi n_i L$, where L is the grating period, $n = 1, 2, \ldots$, into EM radiation. The radiation frequency is determined, in accord with the plasmon dispersion law, by the wave vector value k and by the areal density of electrons in 2D plasma layer. On the other hand, there are theoretical investigations of plasma wave amplification in 2D systems with drifting electrons [3,4]. In this report, the phenomenon of the stimulated coherent EM radiation generated under plasma wave drift instability conditions in the structure with grating is discussed on the basis of theoretical results obtained in a rigorous EM approach elaborated by the authors in [5]. The absolute EM instability develops in the structure when the electron drift velocity exceeds the phase velocity of a spatial Fourier harmonic of the plasma wave in the "cold" (without drift) system. The frequency and temporal increment of generated EM radiation increase with the electron drift velocity. For the realistic characteristic parameters of the structure, EM generation sets in at the electron drift velocities (1-2)$\times 10^7 cm/s$ and the radiation frequencies fall within the far-infrared wavelength range.

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OPTICAL INVESTIGATIONS OF *FREE-STANDING* POROUS SILICON STRUCTURE

Piotr Ziemiański and Jan Misiewicz

Institute of Physics, Technical University of Wroclaw

Wybrzeże Wyspiańskiego 27, 50-370 Wroclaw, Poland

Tel. +48-71-203528 ; Fax +48-71-229696

Silicon is the basic material for electronic but work in optoelectronic is reserved for other semiconductors because crystalline silicon normally emits extremely weak light in the infrared region. The possibility of using silicon , since Canham demonstrated efficient visible luminescence from anodized silicon names "porous silicon" stimulated research in this field. In our work we present results of optical investigation of free-standing porous silicon films. Free-standing porous silicon films give possibility of direct comparision of the photoluminescence and absorption spectra. Free-standing films might also find a broad applications e.g. gas sensors.

Free-standing porous silicon films were obtained by anodization crystalline silicon in a hydrofluoric acid solution. After the anodization process the obtained layer have been immersed in boiling water. The photoluminescence, optical absorption and infrared absorption FTIR measurements were performed. The shift of the photoluminescence spectra and absorption edges to higher energy region was observed. Immersing in boiling water results in oxidation of the surface of the porous silicon microstructure and in decrease of silicon wires dimensions. From FTIR measurements we now that during boiling treatment the silans group which passivate the porous silicon surface will be replaced by agueous oxide like $SiO_2 nH_2O$. Our results confirme that visible photoluminescence from porous silicon is associate not only with quantum size but also with surface composition. Change on the surface after inmersing in boiling water show that for different coverage of surface we have different spectra of the photoluminescence. We may expect that experiments with different surface treatment can solve problem of stability of light emission from silicon.

Dielectric function of a two dimensional electron gas in a weak unidirectional spatially modulated periodic magnetic field

S. M. Stewart, D. J. Fisher, W. Xu and C. Zhang

Department of Physics, University of Wollongong, New South Wales 2522, Australia

The dynamical dielectric response function of a two dimensional electron gas under a perpendicular magnetic field and in the presence of an additional weak unidirectional spatially modulated periodic *magnetic* field is calculated within the random phase approximation. It is found that the dynamical dielectric response function is not only broadened by the additional magnetic modulation, it also contains a series of subsingularities at the band edges. The origin of these new subsingularities is attributed to the magnetic modulation induced broadening of the energy spectrum. This broadening, being non uniform, leads to the reintroduction of particle-hole excitations into the dielectric response function. Such fine structure at the band edges are similar in appearance to those recently reported for the case of a weak unidirectional spatially modulated periodic *electric* potential [1] though however the former can be at least an order of magnitude larger in bandwidth compared to those seen for the *electric* case when equal modulation strengths are considered. It is therefore proposed that these new predicted fine structures should be more readily observed in far infrared spectroscopy experiments over their *electric* counterpart.

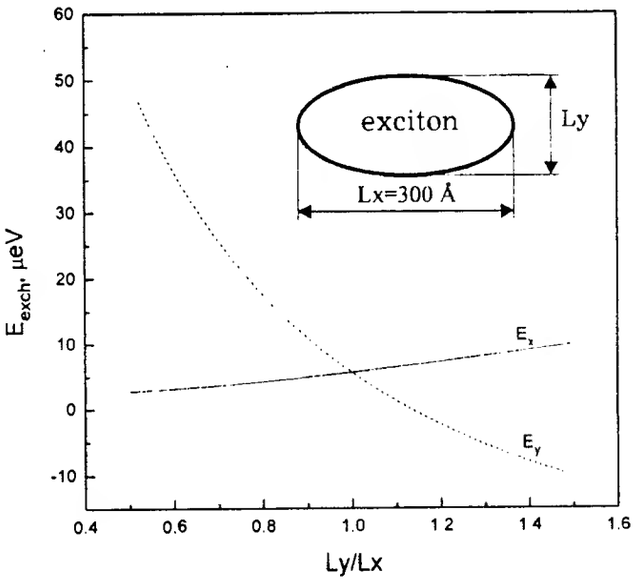
[1] S. M. Stewart and C. Zhang, Phys. Rev. B **52**, R17036 (1995).

ANISOTROPIC EXCHANGE SPLITTING OF EXCITONIC LEVELS IN SMALL QUANTUM SYSTEMS

S.V. Goupalov, E.L. Ivchenko, A.V. Kavokin

A.F.Ioffe Phisico-Technical Institute, 194021, St.-Petersburg, Russia

We have studied theoretically the fine structure of excitonic levels in small quantum systems: (i) localized excitons with laterally-anisotropic envelope function in quantum wells and (ii) free excitons in a grating of quantum wires. It has been shown that in both cases the radiative exciton states are split into two linearly polarized sublevels due to the long-range exchange interaction. Fig. 1 shows exchange energy E_α for the exciton polarized along the axis α as a function of the ratio L_y/L_x where L_α (α=x,y) characterizes exciton envelope extension in the α direction.



In the structures with a grating of quantum wires, the energy of excitons polarized perpendicularly to the wires is almost unaffected by the long-range exchange whereas the energy renormalization for the excitons polarized along the wires can reach few hundred μeV.

Effect of doping density on capacitance of resonant tunneling diodes

J. Jo

Department of Electronics Engineering, Ajou University

Suwon 442-749, Korea

K. L. Wang

Department of Electrical Engineering, University of California

Los Angeles, CA 90024, USA

Capacitance in a double barrier resonant tunneling diode (RTD) is an important parameter in determining high frequency characteristics of the RTD. We studied capacitance in $In_{0.53}Ga_{0.47}As$/AlAs RTD's as a function of the doping density in the emitter and the collector. Capacitance was measured by using LC resonance of an RTD around 500 MHz frequency, where the inductance was provided by the bonding wire. The measured capacitance of a 100 μm diameter RTD decreased from 30 pF to 16 pF as the doping density was lowered from 4.6×10^{17} cm^{-3} to 2.0×10^{16} cm^{-3}. We explain the doping density dependence by considering the shape of the wavefunctions in the emitter and the collector.

The electron density profile was calculated from the Schrödinger equation. The presence of the barriers changes the electron density in the emitter from a uniform distribution into a sinusoidal form, due to reflection from the barriers. Capacitance was calculated from the distance between the leading edges of the wavefunctions in the emitter and the collector. The calculated capacitance showed similar doping density dependence as the measured capacitance. Our calculations also show that the electron density in the quantum well increases with the doping density, and this is in agreement with the observation of low parallel resistance at high doping density. These agreements indicate that the RTD capacitance depends on the doping density due to the electron density modulation around the barriers.

Magnetic Field Dependence of Biexciton Binding in GaAs/(Al,Ga)As Quantum Wells

Kyu-Seok Lee*, C. D. Lee**, Yongmin Kim†, S. K. Noh**, C. H. Perry†, and E. H. Lee*

* Electronics & Telecommunications Research Institute, Yusong, Taejon 305-600, Korea

** Korea Research Institute of Standards & Science, Yusong, Taejon 305-600, Korea

† Northeastern University, Boston, MA 02115, U.S.A.

Recently, biexcitons in GaAs/(Al,Ga)As quantum wells have been the subject of much attention. They have been extensively investigated using time-integrated or time-resolved photoluminescence (PL) techniques, and from exciton-biexciton quantum beats in transient four-wave-mixing experiments. A variety of biexciton binding energies from 0.6 to 2.8 meV have been suggested for different samples by several authors[1]. However, few experimental studies on the magnetic field dependent biexciton binding energies have been reported. In the present work, we present results on a series of magnetophotoluminescence (MPL) investigations of biexciton states in GaAs/$Al_{0.3}Ga_{0.7}As$ quantum wells having well widths of 15, 20, and 25 nm. The low temperature (T = 4.2 K) PL studies of the heavy-hole exciton and the biexciton peaks showed linear and superlinear increase in intensity with the excitation density, respectively. The biexciton binding energy at zero field was determined to be 1.17 ± 0.1 meV for all the quantum wells investigated in this study. In the presence of a magnetic field applied parallel to the growth axis, the MPL biexciton peak intensity decreased with increasing magnetic field. The diamagnetic shift of the biexciton was clearly observed up to B = 9 T; at higher fields it was not possible to clearly resolve the heavy-hole excitons and biexcitons in our experiments. We find that the biexciton binding energy linearly decreases at the rate of 0.079 meV/T. A linear extrapolation of these results to higher fields indicates that biexcitons in GaAs/(Al.Ga)As quantum wells are frozen out at B > 15 T.

[1] R. Cingolani and K. Ploog, Adv. Phys. **40**, 535 (1991); D. Birkedal et al. Phys. Rev. Lett. **76**, 672 (1996), and references therein.

* Work supported in part by the Korea Telecomm. and the Ministry of Communications.

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Optical Determination of Exciton Reduced Masses in (In,Ga)As/AlAs/GaAs Quantum Wells

Kyu-Seok Lee*, Yongmin Kim†, C. D. Lee**, S. K. Noh**, C. H. Perry†, and E. H. Lee*

* Electronics & Telecommunications Research Institute. Yusong, Taejon 305-600, Korea

† Northeastern University, Boston, MA 02115, U.S.A.

** Korea Research Institute of Standards & Science, Yusong, Taejon 305-600, Korea

We have systematically determined exciton reduced masses for a series of In_xGa_{1-x} As/AlAs/GaAs strained quantum wells with the indium compositions of $x < 0.2$. In particular. we have focused on the influence of 0 - 2 barrier layers of AlAs deposited between the (In.Ga)As and GaAs layers. The diamagnetic shift of the photoluminescence (PL) of the exciton ground state was measured at liquid helium temperature (T = 4.2 K) in the presence of a magnetic field up to 50 Tesla applied parallel to the growth axis. Using a variational method, we calculated the binding energy and diamagnetic shift of the exciton ground state. Comparison between the experimental data and theoretical results demonstrates that μ, the exciton reduced mass, increases with the magnetic field. From the electron effective mass (calculated using the effective mass approximation) and μ, we determined the heavy-hole in-plane mass. For (In.Ga)As/GaAs quantum wells, the exciton reduced mass was found to decrease with an increase in either the quantum-well width or the indium composition. Similar behavior was observed for the heavy-hole mass down to the value at the decoupling limit ($m_{hh,\rho} = 0.11\ m_0$) in the presence of a low or medium magnetic field (B < 10 T). For narrow (In.Ga)As wells. the deposition of 1 or 2 monolayer thickness of AlAs at quantum well interface considerablely increased both the energy of band-edge lumiminescence and the exciton reduced mass. For instance. in fields of B ≈50 T. for $x = 0.14$ and well widths of 62. 114, and 216 Å with 0(1) AlAs interfacial layer. we found μ/m_0 having values of ≈0.048(0.057). 0.046(0.051).and 0.044(0.047), respectively.

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† Work supported in part by the National High Magnetic Field Laboratory under NSF Grant DMR 90-16241, State of Florida, and US Department of Energy.

EXPERIMENTAL AND NUMERICALLY SIMULATED RAMAN SCATTERING IN PHOTOLUMINESCENT POROUS SILICON

E. Ribeiro, F. Cerdeira, D. M. Soares and O. Teschke
Instituto de Física "Gleb Wataghin", Universidade Estadual de Campinas, Unicamp, 13083-970, Campinas, SP, Brazil

Recent Transmission Electron Microscopy and Photoluminescence studies suggest that Porous Silicon can be obtained in two distinct morphologies[1]. The first one is composed of isolated cylindrical nanocrystals and the second of an interconnected network of Si crystallites. In both cases the size of the particles is similar, but the connectivity would have a decisive effect on the Photoluminescence efficiency, where the stronger luminescence is exhibited by the samples composed of isolated nanocrystals. In this paper we report on the Raman spectra of both types of structures and analyse our results in the light of the predictions of models which describe isolated or interconnected nanostructures of crystalline Si. Initially we use a one-dimensional linear chain model to simulate the Raman spectra of both morphologies. The model shows that, although in both cases the one-phonon Si Raman line is asymmetrically broadened in relation to that of the bulk Si, connected structures yield lineshapes that are broader and more asymmetric than those of isolated crystallites of the same size. This is precisely the trend observed in the experimental spectra of our samples. Next, three-dimensional phenomenological models (variations of the model of Richter, Wang and Ley[2]) are used with boundary conditions which are compatible either with isolation or connectivity. The experimental lineshapes in both cases are best fitted with crystallites of cylindrical shape with $\sim$ 5 nm in average diameter and a 3:1 length to diameter ratio. In order to explain the position of the Raman line, an expansive strain of $\epsilon \sim 3 \cdot 10^{-3}$ is required. These conclusions are consistent with the earlier work of Teschke *et al.*[1] as well as those of some other authors.

[1] O. Teschke, F. Alvarez, L. Tessler and M. U. Kleinke, *Appl. Phys. Lett.* **63**, 1927 (1993).

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Convective and Absolute Instabilities in Laterally-Confined Semiconductor Superlattices

X. L. Lei

State Key Laboratory of Functional Material for Informatics, Shanghai Institute of Metallurgy Chinese Academy of Sciences, 865 Changning Road, Shanghai 200050, China

The demonstration of Esaki-Tsu negative differential mobility (NDM) in superlattice vertical transport, has stimulated new interest in possible instabilities in semiconductor superlattices. Early investigations of unstable space-charge-wave (SCW) modes and absolute instabilities in systems exhibiting NDM were carried out mainly for bulk GaAs in associate with Gunn effect, using exclusively the one-dimensional drift-diffusion (DD) model. A recent analysis of vertical transport in planar superlattices based on a three-dimensional (3D) nonlinear hydrodynamic balance-equation (HBE) method, yields results significantly different from those of the DD model. For a typical GaAs-based unconfined (planar) superlattice the HBE method predicts a SCW propagating at a phase velocity ranging from 0.75 to 0.95 that of the carrier drift velocity and having an amplitude growth rate only about 1.9 to 3.8 percent of that predicted by the DD model. Moreover, it predicts occurrence of absolute instability only when system is biased deep in the NDM regime, while in the DD model an absolute instability occurs immediately when the system exhibits NDM.

This presentation reports a systematic analysis of SCW modes and absolute instability in laterally confined semiconductor superlattices, using the three-dimensional HBE approach with accurate microscopic treatment of phonon and impurity scatterings. For superlattices with transverse diameter d_r varying from 10 to 40 nm, we find amplitude-growth space-charge-wave modes which propagate at a phase velocity ranging from less than 0.1 to 0.95 that of the carrier drift velocity and with an amplitude-growth rate much larger than that in an unconfined superlattice, but still no more than a few tenth that predicted by the conventional DD model. On the other hand, absolute instability begins to occur at a smaller reduced bias field in confined systems than in unconfined ones. In the strongest confined case investigated ($d_r = 10$ nm), the system becomes absolute unstable immediately after it enters the NDM regime.

Plasmon Satellite Peak Observed in Photoluminescence Spectra of n-Type Modulation-Doped GaAs/AlGaAs Heterostructures

S.J.Xu, B.S.Wang, H.Z.Zheng, W.C.Cheng, K.J.Luo, J.Liu

National Laboratory for Superlattices and Microstructures,
Institute of Semiconductors, Academia Sinica
P.O.Box, Beijing 100083, P.R.China

We reported a plasmon satellite peak in photoluminescence (PL) spectra, related to two-dimensional electron gas (2DEG) in a modulation-doped GaAs/$Al_{0.3}Ga_{0.7}As$ single heterostructure ($n=6.1 \times 10^{11}cm^{-2}$, $\mu = 8.3 \times 10^{4}cm^{2}/V.Sec$ at 77K). Three spectrum peaks showed up at the energy positions of 1.52eV (peak A), 1.494eV (peak B) and 1.513eV (peak P) as measured at 6K. Peak B was assigned as the donor-acceptor transition associated with the carbon, C(D,A), and partially confirmed by its quenching at an elevated temperature of 55K. Peak A stemed from the radrative recombination of 2DEG with localized holes at acceptors near hetero interface. At 6K peak A exhibited an asymmetrical lineshape with a sharp cut off on the high energy side. As the temperature rised gradually up to 30K, its peak intensity was depressed, and the maximum PL intensity was red-shifted, leaving a long tail on the high energy side. This features the behaviour of Fermi edge singularity (FES), indicating the importance of many body effect in our sample. The most striking feature of our observation is the continuous redshift of peak P from 1.513eV to 1.480eV by increasing excitation power from $0.05mW/cm^2$ up to $100mW/cm^2$. In spite of it's closeness to the transition of bound excitons, (D,X) or (A,X), at low excitation level (1.515eV or 1.513eV respectively), neither (D,X) nor (A,X) could account for a red shift as large as 32meV with the excitation power. The other possible causes, like the filling of photoelectrons at the interface potential well might lead to a blue shift, which was presumably canceled by band-gap renormalization, as evidenced by the invariance of peak A's position. We attributed peak P to the emission of plasmon of collective excitation caused by shak-up process of 2DEG near the Fermi edge. In ordinary quantum well a 2D plasmon dispersion, $W^{2D}_{p} \propto q^{1/2}$, makes it impossible to see a distinguishable satellite in PL spectra. However, our theoretical work, which will be published else where, verified that the spatially separated photoholes, although could not participate the photoemission, were still coulomb-interacted with 2DEG. As a result, a peculiar coupled plasmon mode formed by 2DEG and separated 3D free holes in GaAs buffer layer may take place, leading to the observed behavious of peak P. The critical issue was that the shake up process due to the perturbation of photoexcited holes not only caused the occurence of FES, but also gave rise to plasmon excitation. Actually, such plasmon side-band was previously reported in x-ray spectra of some metals and insulators. To our knowledge, such plasmon emission related to 2DEG was first observed so far.

Double barrier coherent sound generator: a new device

Diana E. Tuyarot, Sergio S. Makler and Enrique V. Anda

Instituto de Física, Universidade Federal Fluminense,

Campus Praia Vermelha, Av. Gal. Milton Tavares de Souza s/n,

CEP 24210-340, Niteroi-RJ, Brazil

and

Mikhail I. Vasilevskiy

Faculty of Applied Physics, N. Novgorod University, 603600 Russia

In recent works[1,2] we proposed a new device, that we called SASER, consisting in a double barrier heterostructure (DBHS) designed to generate ultra-high-frequency coherent sound. The device is tailored so that under the effect of an external bias, part of the electrons injected into the first excited level decay to the ground state by emitting LO-phonons.

Due to the low energy and short wavelength of the phonon beam this device can be used for imaging, for non-destructive characterization of nanostructures and to build phonoelectronics systems (analogous to optoelectronics).

In this paper, to calculate the electronic current we use a simple model that takes into account the electron-phonon and the electron-electron interactions. The electronic part is described in terms of a tight-binding Hamiltonian. The lattice dynamics is represented by a single LO-phonon mode confined inside the well for the primary beam and another single TA-phonon mode for the secondary one[3]. The electron-phonon interaction is described by a single transition matrix element between the two lowest states localized at the well. The electron and phonon populations, the current and the potential profile are calculated selfconsistently.

The results confirm the viability of the device, predicted in previous simplified calculations[2].

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Electron transport across GaAs/AlGaAs graded barrier structures

P.J. Bishop, M.E. Daniels and B.K. Ridley

Department of Physics, University of Essex, Wivenhoe Park, Colchester, CO4 3SQ, UK.

J.S. Roberts and G. Hill

EPSRC Central Facility for III-V Semiconductors, Department of Electronic and Electrical Engineering, The University of Sheffield, Mappin Street, Sheffield, S1 3JD, UK.

Abstract

Electron transport over short n^+ GaAs / $Al_xGa_{1-x}As$ / n^+ GaAs barrier structures with graded interfaces has been investigated both theoretically and experimentally. The central AlGaAs region contained doped GaAs quantum wells. The barriers between the wells had a thickness in the range 7.7 to 31nm. The Fermi level, which was defined by the carrier density in the contacts, was pinned in the central region by the doped wells. This eliminated the increase in barrier height observed in plain AlGaAs barriers, which is caused by background space-charge. At high temperatures and low electric fields, where tunnelling is limited by the graded barriers, the conduction has been modelled successfully using drift-diffusion theory. Good agreement between experimental data and theory has been obtained in plots of current as a function of both voltage and reciprocal temperature. The three regions, graded interface / central region with wells / graded interface, function like three resistors in series. The resistance of the central region dominates, which results in a field of $40kVcm^{-1}$ in this region when 400mV is applied across the sample. An increase in the density of wells allows tunnelling to occur at lower fields and higher temperatures. The contribution made by tunnelling to the current has been investigated in the sample with 7.7nm barriers. When only tunnelling is considered the resistance of the graded regions dominates the conduction.

FAR-INFRARD RESONANT-ABSORPTION BY HOT-ELECTRONS IN AlGaAs/GaAs-BASED TWO-DIMENSIONAL ELECTRON SYSTEMS

W. Xu, C. Zhang and S.M. Stewart
Department of Physics, University of Wollongong, NSW 2522, Australia

With the development and application of state-of-the-art techniques such as free-electron-lasers (FELs), it has become realistic to study transport of two- dimensional electron gases (2DEGs) driven by intense terahertz (THz) or far-infrard (FIR) electromagnetic radiations.[1,2] A THz-driven 2DEG is a quantum system with different competing energies (frequencies), where the electronic subband energy, electron kinetic energy, Fermi energy, phonon energy, photon energy, plasmon energy, etc. are on the meV (THz) scale, so that the quantum resonance effects can be observed. The results obtained from recent experimental measurements[1] have shown that in AlGaAs/GaAs-based 2DEGs, an *unexpected* peak in absorption of the electromagnetic radiation can be clearly observed around $\omega/2\pi \sim 0.5$ THz (ω the photon frequency) at moderate electron temperatures ($T_e \sim 80$ K). This phenomenon cannot be explained by mechanisms such as inter-subband absorptions and hot-plasmon absorptions.

In this paper, we propose a mechanism which is responsible for the experimental findings reported in Ref. 1. Through calculating the frequency-dependent conductivity in the nonlinear response regime, where electron interactions with impurities and with acoustic- and LO-phonons are included, we find that the inverse of the relaxation time ($1/\tau$ or scattering rate) of the device system is *also* on the THz scale so that: 1) the THz radiation may modify strongly the processes of electron momentum and energy relaxation; 2) $1/\tau$ always decreases with increasing ω; and 3) the competition between ω and τ will result in a change-over of the dependence of electromagnetic absorption on the photon frequency. Consequently, a peak in the resonant-absorption can be observed. Our results show that: i) electron−LO-phonon scattering is responsible for the resonant-absorption: ii) when $T_e > 150$ K, the peak becomes greatly suppressed. i) and ii) are the main reasons why the resonant-absorption occurs at moderate electron temperatures; iii) the absorption peak can only be observed in the hot-electron regime where the value of $1/\tau$ is much larger than that at linear response. When $T = T_e$, the intensity of the absorption always decreases with increasing ω; and iv) FIR resonant-absorption at different frequencies (0.2 - 0.6 THz) can be tuned by heating the electrons to different temperatures (40 - 150 K). This effect may be used for frequency-tunable FIR detectors. The resonant-absorption proposed in this study is a consequence of electronic transitions accompanied by phonon-emission and optical-absorption via electrically heated electrons in the device systems, which is a non-zero temperature and nonlinear electron transport effect.

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Structural Phase Transitions in the Two-Dimensional Wigner Crystal in a Lateral Superlattice

A.O.Govorov

Institute of Semiconductor Physics, Russian Academy of Sciences
Siberian Branch 630090, Novosibirsk-90, Russia.

Electronic phase transitions in quantum dot arrays are discussed in the current literature [1,2]. In the present report, we consider instability of a two-dimensional (2D) Wigner crystal in a laterally modulated electrostatic potential. Two models of an electron system are considered: 1) a wide electron channel including a 2D Wigner crystal and 2) a short-period lateral 1D superlattice with interacting electron Wigner chains. To find instability, we calculate the spectrum of elementary excitations (phonons) in an electron lattice and investigate the behavior of soft modes. Electron channels with a controlled confinement potential can be realized in the quantum well system with an interdigitated gate [3]. In such a system the screening effect of the metallic gate leads to the confinement potential with a flat bottom, while the effective width of an electron channel can be varied by the voltage. The electron lattice can be compressed with reducing the width of the channel. We find that the transversal phonon mode of compressed Wigner crystal gets soft when the deformation of the electron lattice exceeds the critical value. The critical value of deformation is about 15%. Thus, the compression of the electron lattice results in the instability and in possible phase transition with breaking axial symmetry of the electron system. For the case of a short-period lateral superlattice including an electron crystal, we find that one of transversal phonon modes shows the soft behavior at non-zero wave vector. The latter indicates the formation of a charge-density wave. The period of the charge-density wave depends on the amplitude of potential modulation and on the electron density. The period of lateral superlattice is assumed to be about 400-500 $\AA$. It was shown recently [4] that the modulated microstructures with periods down to 100 $\AA$ can be fabricated using the atomic-force microscope technique. The electron crystal in a microstructure can be stabilized in high magnetic fields. We note that instability found in this work is impossible in quantum dot arrays because of the electron motion confinement in all directions. The structural phase transitions can lead to specific features in the light absorption spectrum [2] and in the voltage-dependency of capacitance [5].

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5. A.O.Govorov, *ibid*, p.503.

Quantum Coupled Architectures for Logic Circuits: Issues, Problems and Experimental Progress

S. Bandyopadhyay
Department of Electrical Engineering, University of Nebraska
Lincoln, Nebraska 68588, USA[1]

V. P. Roychowdhury
School of Electrical Engineering, Purdue University
West Lafayette, Indiana 47907, USA

We have recently proposed a number of quantum coupled architectures utilizing single electron effects in quantum dots to realize nanoelectronic computational modules[3]. In this talk, we will explore various issues pertinent to the design of Boolean logic circuits based on such paradigms. The lack of isolation between the input and output of logic devices presents a serious impasse which seems to restrict the size of the circuits and favors a modular approach. We will also explore the possibility of realizing dissipationless logically reversible gates (such as the Feynman CONTROLLED NOT gate and the Toffoli gate) using single electron effects in quantum dots.

Finally, experimental progress towards self-assembling these circuits by chemical means will be discussed.

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[1]On leave from the University of Notre Dame, Notre Dame, Indiana 46556, USA

[2]Supported by NSF and ARO

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MoB Intersubband processes in quantum wells and superlattices

INTERMINIBAND ELECTROLUMINESCENCE AND LASER ACTION IN SEMICONDUCTOR SUPERLATTICES

G. Scamarcio, F. Capasso, J. Faist, C. Sirtori, A. L. Hutchinson, D. Sivco, and A.Y.Cho
Lucent Technologies Bell Laboratories , Murray Hill, NJ 07974, U. S. A.

We report the first observation of interminiband electroluminescence in superlattices (SL). Previously, only inter-miniband absorption was reported[1]. The heterostructures, grown by MBE on InP substrate consist of several stages each comprising a GaInAs/AlInAs SL followed in the growth sequence by a digitally graded pseudo quaternary alloy layer which serves as an electron injector into the SL active regions. For the electroluminescence studies two SL structures with well/barrier thicknesses 40Å/26Å (A) and 60Å/18Å (B) have been investigated. In both cases the width of the 1st miniband is $\Delta_1 \approx 50$meV. The energy gap E_g occurring at the edge of the SL mini-zone and the width Δ_2 of the 2nd miniband are $E_g \approx 250$ meV, $\Delta_2 \approx 140$meV (sample A), and $E_g \approx 160$meV and $\Delta_2 \approx 90$meV (sample B). The intentional doping of the SL's corresponds to a calculated quasi-Fermi level $E_f^* = 12$ meV above the bottom of the 1st miniband at zero bias. The samples were processed into mesas and microsecond long voltage pulses in the range 0-5V were applied across the structure. Above an onset of ~ 1.5 V a current of several hundreds mA flows through the structure, inducing luminescence observable up to room temperature with optical powers in excess of 10 nW. The radiation is strongly polarized normal to the SL layers, as expected from interminiband selection rules. A linear relationship between optical power and injected current is measured. The luminescence spectra are strongly bias dependent and show features ascribed to critical points in the miniband joint density of states. At low bias a single narrow peak corresponding to the inter-miniband energy gap $E_g(k_z=\pi/d)$ is observed. At larger bias higher energy inter-miniband radiative transitions produce an asymmetric broadening on the high-energy side of the main peak with a wide (~160 meV) shoulder and a cut-off corresponding to the lowest energy holes in the 1st miniband. Laser action corresponding to transitions at $E_g(k_z=\pi/d)$ is observed up to 240 K in pulsed operation in device structures including AlInAs cladding layers to create a waveguide and optical feedback. A very high peak power ($P > 0.8$ W at 10K) is measured. A comparison with quantum cascade lasers based on transitions between *localized* states of double quantum wells will be made.

1. For a recent review see e. g. Manfred Helm, Semicond. Sci. Technol. 10, 557 (1995)

Optically pumped mid-infrared intersubband emission and lasing in coupled quantum wells

A. Sa'ar and Y. Lavon
Division of Applied Physics, The Fredi and Nadine Herrmann School of Applied Science, The Hebrew University of Jerusalem, Jerusalem 91904, Israel.
F. H. Julien and P. Boucaud
Institut d'Electronique Fondamentale, URA 22 CNRS, Bat 220, Universite Paris XI, 91405 Orsay Cedex, France.
J. Wang and J.-P. Leburton
Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
R. Planel
Laboratoire De Microstructures et Microelectronique, CNET-Bagneux, 196 Av. H. Ravera, 92225 Bagneux Cedex, France.

Summary

Mid infrared semiconductor lasers that are based on population inversion between conduction subbands of a quantum well (QW) structure have attracted much attention recently. Faist *et al* [1] demonstrated the operation of the quantum cascade laser which is a unipolar intersubband injection laser. Another scheme to generate population inversion between conduction subbands is by optical pumping [2]. In this contribution we summarize our recent experimental and theoretical results including the observation of mid-infrared emission from a GaAs/AlGaAs coupled QWs (CQW) structure [3-4] (see Fig.1).

The heart of our structure consists of an asymmetric highly coupled QWs with three confined subbands that are involved in the emission process. The structure was designed so that free carriers can optically be excited from the ground subband into the third subband by a CO_2 laser. The optical emission transition occurs between the third and the second subbands, and the final stage of the emission process involves a fast phonon assisted relaxation of the carriers into the ground subband.

In our experiments the CQW structure was pumped by a 9.2 μm laser radiation. We have observed spontaneous emission at 14 μm that persists up to room temperature with a maximum at 190 K. In lightly doped samples we measured a radiative efficiency of about 60 nW/W. Based on these results we predict that our structures could be very effective for achieving almost complete population inversion and large stimulated gain.

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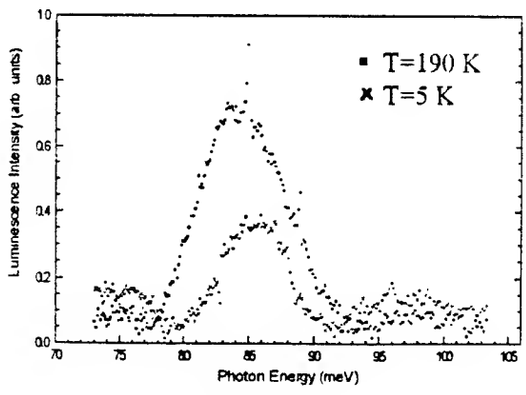

Fig.1: The emission spectra at 5K and at 190K

INTERSUBBAND SCATTERING RATES IN GaAs QUANTUM WELLS, MEASURED BY FEMTOSECOND LUMINESCENCE

M. Hartig, S. Haacke and B. Deveaud
Laboratoire d'Optoélectronique Quantique, EPFL, CH1015 Lausanne, Switzerland
R.A. Taylor and L. Rota
University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK

We have studied intersubband relaxation in a series of GaAs quantum wells using photo luminescence upconversion. The advantage of this technique is that, even with a very short time gate ~ 100 fs, we can get a direct image of the electron and hole distributions with excellent sensitivity, down to very low excitation densities. This is a considerable step forward compared to previous work, as we can directly monitor the gradual transition from a non-equilibrium to an equilibrium carrier distribution and the development of intersubband scattering under these conditions. We use laser energies from 2 eV down to resonant excitation within the different subbands and a variety of excitation densities down to ~ 10^{10} cm^{-2}.

A typical spectrum is shown on Fig. 1, which contains the main features of luminescence at very short times. The n=1 and n=2 transitions are clearly in evidence, the carrier distribution is not fully thermalized and the temperature of electrons in the n=2 subband is higher than in the n=1 one. Our study is mainly concentrated on the temporal behavior of the n=2 luminescence intensity. A typical time behavior of this luminescence line is depicted in Fig. 2 (due to nonlinear effects the decay time does not directly measure the intersubband relaxation time). The relaxation time gained from these spectra depends to a great extend on the experimental conditions, such as excitation energy and excitation density. The dependence of effects like intervalley scattering, the strength of carrier-carrier scattering, Fermi filling or hot phonon effects on these parameters could be fully understood, which helps us to understand contradictory results obtained by other groups.

The complexity of the different processes involved led us to compare our spectra to an ensemble Monte Carlo simulation. The intersubband electron scattering times predicted by this model are of the order of 600 fs for 100 Å QWs, and the experiment is precisely reproduced for all densities. The predicted wavevector dependence of the intersubband scattering rate is observed for the first time. Results of two color upconversion experiments which allow a resonant excitation of the n=2 transition will be presented.

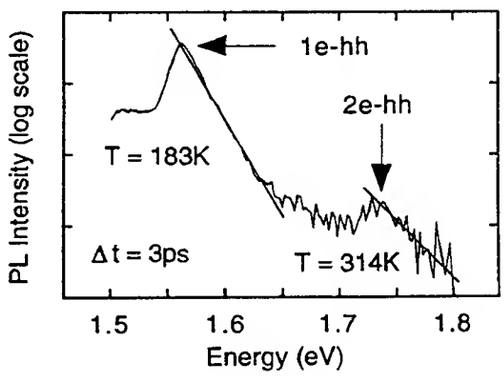

Fig. 1. Energy resolved spectrum of a GaAs MQW sample.

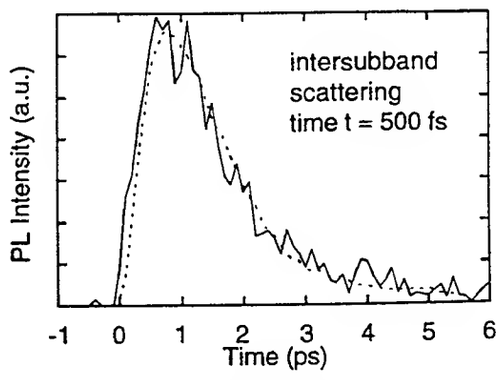

Fig. 2. Time resolved intensity of the n=2 transition and Monte Carlo simulation.

Mid-Infrared Femtosecond Spectroscopy of Intersubband Hot Carrier Relaxation in Quantum Wells

P. M. Fauchet, Ju. V. Vandyshev, J. M. Russell, Z. Xu, and G. W. Wicks
Department of Electrical Engineering and The Institute of Optics, University of Rochester, Rochester, NY 14627

We have performed direct measurements of the relaxation time of holes (electrons) in p-type (n-type) quantum wells (QWs) using femtosecond mid-infrared laser pulses tuned on resonance with the intersubband transition energy. Most of the measurements have been performed in the degenerate pump-probe configuration as a function of carrier density, sample temperature, laser wavelength, laser intensity, and well design. The samples are strained InGaAs QWs.

In all our experiments, bleaching of the transition recovers as a single exponential with a time constant τ that depends on several parameters. In p-type samples with a sheet density of 10^{13} cm^{-2}, the maximum bleaching is linear with pump intensity below 1 GW/cm^2 and saturates to ~3% with a saturation intensity I_{sat} of 3 GW/cm^2. As the saturation regime is entered, τ increases from 0.6 ps to 1.8 ps. When T decreases from 300 K to 77 K, τ increases, consistent with a rate that varies as (2n+1) where n is the Bose-Einstein occupation number. When the laser wavelength is tuned through the absorption band, the magnitude of the signal changes but its temporal behavior does not change within the accuracy of the measurements. The shape of the bleaching recovery is insensitive to the laser wavelength inside the absorption band and to the hole sheet density from 10^{12} cm^{-2} to 10^{13} cm^{-2}. Results in n-type samples show interesting differences and similarities with p-type samples, which will be discussed in the presentation.

Detailed calculations of the various intersubband scattering rates, including screening and guided phonons, indicate that in the p-type sample τ measures the scattering time out of the excited (lh) state. This is in contrast to n-type QWs, where carrier cooling may play a dominant role. The recovery of the ground (hh) state is accessed from experiments in the saturation regime, where nearly 50% of the holes have left the hh subband and τ increases. We will present the results of similar experiments performed on more complicated structures such as asymmetric coupled QWs and a different type of experiments designed to measure simultaneously the excited state deexcitation and the ground state recovery, which will put very tight constraints on the theoretical models.

We acknowledge support from the ONR through contracts N00014-92-J-4063 and N00014-91-C-0170, and the National Science Foundation through grant ECS-9413989.

Energy relaxation of hot electrons in GaAs/AlGaAs superlattices measured by infrared differential spectroscopy

W. Hilber[1], M. Helm[1], K. Alavi[2], R. N. Pathak[2]

[1]*Institut für Halbleiterphysik, Universität Linz, A-4040 Linz, Austria*

[2]*Center for Advanced Electron Devices and Systems, Department of Electrical Engineering, The University of Texas at Arlington, Arlington, TX 76019, USA*

We have previously shown that the inter-miniband absorption spectrum of a superlattice is strongly temperature dependent, when the Fermi energy at low temperature lies in the first miniband [1]. Here we apply this temperature dependence to study the energy relaxation of hot electrons in a $GaAs/Al_{0.3}Ga_{0.7}As$ superlattice of 75 Å well width and 25 Å barrier width, homogeneously doped to $n = 6 \times 10^{16}$ cm^{-3}. The knowledge of the energy relaxation in such superlattices may be of key importance for the realization of electrically driven Bloch oscillators.

At a lattice temperature of 10 K voltage pulses shorter than 10 μs are applied parallel to the superlattice layers and cause the electron gas to be heated up to a certain electron temperature, T_e, hot electrons now occupying states at the edge of the mini-Brillouin zone. The change of the inter-miniband absorption spectrum during the pulses is measured with a step-scan Fourier-transform infrared spectrometer. These measurements are compared to absorption spectra taken at different lattice temperatures, thus enabling a calibration of the electron temperatures. Hence we obtain the electron temperature and the energy loss rate (power loss) as function of the applied electric field, E. In the present experiment we cover electron temperatures from 15 to 45 K, which is the cross-over regime from acoustic-phonon to optical-phonon dominated energy relaxation. Comparison with calculations of the energy loss rates suggests that plasmon-phonon modes also contribute to the relaxation.

In addition, we have calculated the phenomenological energy relaxation time, τ_ε, from the power balance, $e\mu E^2 = (\langle\varepsilon(T_e)\rangle - \langle\varepsilon(T_L)\rangle)/\tau_\varepsilon$, where the full superlattice band structure has been used to evaluate the mean energy. Note that we are in a regime where neither the usual low- nor high-temperature approximations are valid. A continuous decrease of τ_ε from 800 ps at 15 K to 40 ps at 45 K is deduced from the data.

We would like to point out that the employed spectroscopic technique for studying the energy relaxation has not been used before, and also there are, to the best of our knowledge, no published data about energy relaxation in strongly coupled superlattices.

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Quasistatic and Dynamic Interaction of High-Frequency Fields with Miniband Electrons in a Semiconductor Superlattice and Intraminiband Relaxation

S. Winnerl[1)], E. Schomburg[1)], J. Grenzer[1)], I. Lingott[1)], H.-J. Regl[1)], A.A. Ignatov[1)], A.D. Semenov[1)], K.F. Renk[1)], D.G. Pavelev[2)], Yu. Koschurinov[2)], B. Melzer[3)], V. Ustinov[3)], S. Ivanov[3)], S. Schaposchnikov[3)] and P.S. Kop'ev[3)]

[1)]Institut für Angewandte Physik, Universität Regensburg, 93040 Regensburg, Universitätsstr. 31 Germany; [2)]Department of Radiophysics, Nizhny Novgorod State University, Russia

[3)]Physico-Technical Institute (Ioffe -Institute), St. Petersburg, Russia

We report on quasistatic and dynamic interaction of high-frequency fields (of frequency ω) with miniband electrons in a semiconductor superlattice that showed a negative differential conductance. The measurements have been performed at room temperature. We also present an analysis using a semiclassical model [1] on the basis of Bloch oscillations of the miniband electrons that allows us to determine an average intraminiband relaxation time τ.

We have studied, for a doped GaAs/AlAs superlattice with a wide miniband (width ~50 meV), the response, namely the reduction of current under the influence of a high-frequency field. We induced high-frequency fields inside the superlattice by coupling in the radiation generated with either backward wave oscillators or a high-power pulsed Raman laser. We found that for $\omega\tau < 1$ and for small high-frequency field amplitudes maximum response occurs at a bias voltage where the second derivative of the static current-voltage characteristic had a maximum, with the maximum of the response being shifted to higher voltages for larger high-frequency field amplitudes. At high frequencies $\omega\tau > 1$ the maximum response occurred at the bias voltage of maximum current for all high-frequency field amplitudes. From our experiments performed for frequencies between 100 GHz and 4 THz we conclude that τ was, for our sample, of the order of 10^{-13} s at T = 300 K.

Our analysis indicates that elastic and inelastic scattering frequencies of miniband electrons were of the same order of magnitude and that the interaction of the high-frequency field with miniband electrons was quasistatic for $\omega\tau < 1$ and dynamic for $\omega\tau > 1$. In the dynamic case we show that in the range of negative differential conductance the dynamics of the miniband electrons coincides with the concept of coherent motion of electron wave packets performing frequency modulated damped Bloch oscillations.

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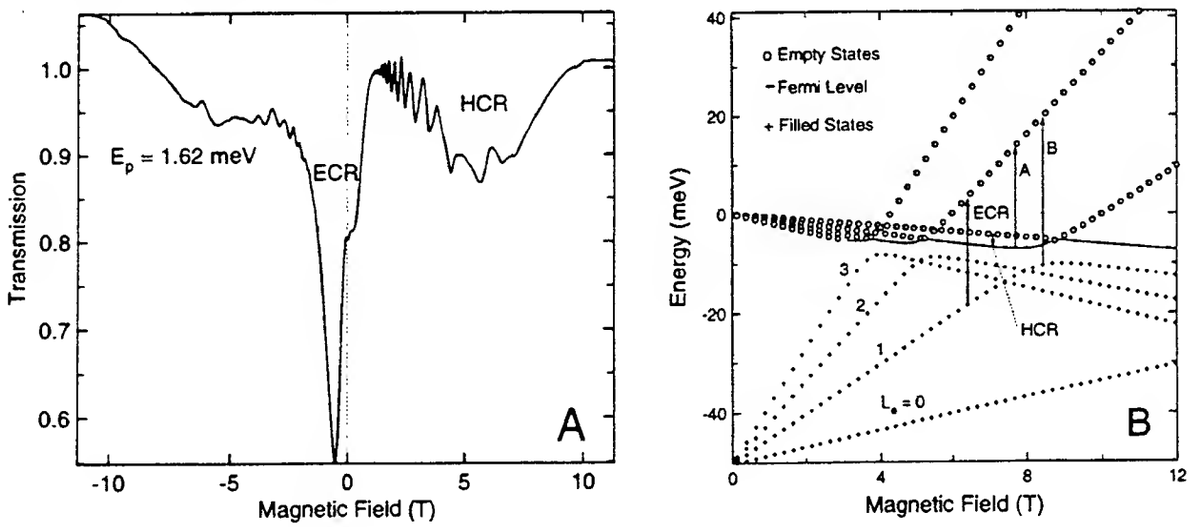
MoC Electronic and optical properties of quantum wells and superlattices

Electron-Hole Hybridizing in InAs Single Quantum Wells Clad with GaSb,

R.J. Wagner, B.V. Shanabrook, M.J. Yang and J.R. Waterman,

Naval Research Laboratory, Washington, DC, 20375-5347, USA

An optically-pumped far infrared (FIR) laser magneto-optical spectrometer has been used to examine electron/hole hybridization in single quantum wells of InAs clad with GaSb. For InAs well thickness greater than 10 nm, the InAs conduction subband lies below the GaSb valence subband. This gives rise to strongly non-parabolic band structure. The resulting magneto-optical spectra can roughly be classified as "interband-like" and "intraband-like". Experiments with circularly polarized radiation have shown strong absorption in the electron active sense near $0.04m_e$ (ECR in Figs. A and B) and in the hole active sense near $0.3m_e$ (HCR in Figs. A and B). However, these resonant features are elements in series of absorption lines (Fig. A) equally spaced when plotted with inverse magnetic field. These lines, which can be observed on either side of ECR, depending on laser photon energy, vary in field position with energy but do not track with ECR. They are more intense near the CR lines and when the heterointerfaces are InSb-like rather than GaAs-like. This suggests a consistent point-of-view of all of the data, namely that all observed lines arise from CR-like selection rules. At magnetic fields/photon energies far from either ECR or HCR, the absorption line intensity is reduced for two reasons: 1. Transition probabilities are reduced since the initial state and the final state have opposite (e or h) character. 2. Transition blocking due the Fermi level position (E_F) in the Landau levels. When E_F is near the hybridized gap energy, we have directly observed modifications to the ECR line position due to hybridization. Since this effect is weak, it could only be unambiguously identified through the use of temperature-dependent (4.5-30K) studies on the lowest Landau levels. Nonetheless, we have observed both the curvature in line position that occurs when the rapidly moving hybridized ECR (Line A in Fig. B) approaches the "classical" ECR position and the second, "across the gap" transition (Line B in Fig. B).



Coupled ultrathin InAs layers in GaAs as a tool for the determination of band offsets

J. Brübach, A.Yu. Silov, J.E.M. Haverkort, W. v.d. Vleuten, and J.H. Wolter

COBRA Interuniversity Research Institute, Eindhoven University of Technology,

Department of Physics, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

We have studied the impact of coupling on the electronic structure of ultrathin InAs layers embedded in a GaAs matrix. The MBE grown samples contain two ultrathin InAs layers separated by a GaAs barrier with a thickness of 4, 8, 16 and 32 monolayers (ML), respectively. An additional reference sample comprises a single InAs layer. The x-ray rocking curves of the coupled InAs layers show a significant destructive interference in the Pendellösung oscillations. The analysis consistently reveals for the whole set of samples that each InAs layer has an average thickness of 1.10±0.05 ML. The photoluminescence spectra show a 70 meV red-shift of the heavy-hole (*hh*) exciton level when the barrier thickness is reduced from 32 to 4 ML. In the photoluminescence excitation (PLE) spectra we observe for the first time in this material system the whole set of symmetric and antisymmetric *hh*- and light-hole (*lh*) states as well as an anticrossing between the antisymmetric *hh*- and the symmetric *lh*-state (see Fig.). The different transitions were classified by a polarization analysis of our cleaved side PLE measurements. Since the splitting between the symmetric and antisymmetric *hh*-states for the weakly coupled layers (32 ML barrier) is entirely due to the splitting in the conduction band, we experimentally find a conduction band offset of 530 meV. From the observed shift and splitting of the *hh*- and *lh*- transitions in the 16, 8 and 4 ML barrier samples we deduce the valence band offset of 385 meV and a strain induced splitting between the *hh*- and *lh*-subbands of 160 meV. Our results are in a good agreement with elasticity theory but significantly differ from the values reported by other groups.

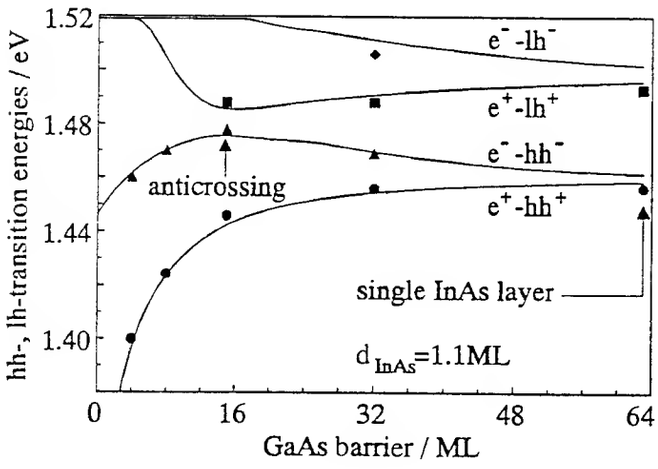


Fig.: In PLE observed transition energies of the coupled ultrathin InAs layers with different GaAs barrier thicknesses. The measured values plotted for a 64 ML barrier belong to the reference sample. At a barrier thickness of 16 ML the anti-crossing between the symmetric *lh*-state (lh^+) and the antisymmetric *hh*-state (hh^-) occurs. The solid lines show calculations in which the confining potential of each InAs layer is described by a δ-potential.

Quasibound states induced by AlAs monolayers in (In,Ga)As/GaAs quantum wells

C. D. Lee, and S. K. Noh
Korea Research Institute of Standards and Science, Taejon 305-600, Korea
Kyu-Seok Lee
Electronics and Telecommunications Research Institute, Taejon 305-600, Korea

The bound and quasibound states induced by insert of ultrathin AlAs layers in (In,Ga)As/GaAs quantum wells were studied through the 4.2K photoluminescence(PL) and photoreflectance spectrscopy(PR). For a single quantum well there exists extended states in the above-barrier. As there is no abrupt change in the density of state in these structure, one cannot observe discrete subband transitions of PR in the above-barrier. In periodic superlattices, extended minibands are developed in the above-barrier states under the Kronig-Penney model. Thus most of studies for such states are related to Type-I and Type-II superlattices. In this presentation we have studied the bound and quasibound states in (In,Ga)As/GaAs quantum wells that have four quantum wells, L_w=1.5, 7, 12, 22 nm. Each well is bordered on each side by 2ML-wide AlAs layers.

In 4.2K PL spectra, a large blue-shift of 1s excitonic emissions was observed for (In,Ga)As/GaAs QW's having 2ML-wide AlAs layers due to the enhancement of quantum reflectivity. On the other hand, the intensity of GaAs excitonic emission is enhanced as increasing the AlAs thickness. From this experimental results it is expected that which the exciton delocalization from (In,Ga)As well to GaAs barrier happens.

To investigate the existence of quasibound states in detail room-temperature PR experiment was performed and its PR spectra of (In,Ga)As/GaAs QW's without and with 2 ML AlAs layers are shown in Fig. 1. The solid circles are experimental data and the solid curves are fitted results by using the well-known third derivative formula. The QW sample without any AlAs layers(Fig.1(a)) shows no distinctive features above the GaAs bandgap energy, while others with AlAs layers(Fig.1(b) and (c)) reveal a series of oscillatory peaks. As undoped quantum wells have flat-bands and the inclusion of AlAs layers do not modify such properties, this experimental result can not be explained by the Franz-Keldysh oscillations which originate from surface electric field effect. It is expected that the inclusion of ultrathin interface layers induces the non-periodicity effect in the superlattices which reduces the interbarrier coupling, and consequently builds up localized subbands in GaAs barrier layers. More evidently, for the PR spectra of two (In,Ga)As/AlAs/GaAs samples with L_b = 50 and 100 nm in Fig. 1(b) and (c), the energies of oscillation peaks in PR spectrum reveal quadratic behavior with respect to indices n=1,2,3... This results indicate that the inclusion of AlAs interface layers supports the formation of quantized above-barrier subbands.

Extremely flat interfaces in $In_{0.04}Ga_{0.96}As/Al_{0.3}Ga_{0.7}As$ quantum wells grown on (411)A $In_{0.04}Ga_{0.96}As$ substrates by MBE

S. Hiyamizu[1], T. Saeki[1], T. Motokawa[1], S. Shimomura[1], T. Kitada[1], A. Adachi[2], Y. Okamoto[3], T. Kusunoki[4], K. Nakajima[4] and N. Sano[5]

1) Faculty of Engineering Science, Osaka University, Toyonaka, Osaka 560, Japan
2) R&D Division, Nissin Electric Co. Ltd., Umezu-Takasecho-cho, Ukyo-ku, Kyoto 615, Japan
3) Research Headquarters, Kubota LTD., Amagasaki, Hyogo, 661, Japan
4) ULSI Crystals Lab., Fujitsu Labs. LTD., 10-1 Morinosato-Wakamiya, Atsugi 243-01, Japan
5) Faculty of Science, Kwansei-Gakuin University, Nishinomiya, Hyogo 662, Japan
Phone: +81-6-850-6455, Fax: +81-6-845-4632, E-mail: hiyamizu@mp.es.osaka-u.ac.jp

InGaAs ternary substrates have high potential for high quality epitaxial growth of wider range of III-V compound semiconductor materials with various lattice constants, and they have been successfully applied to InGaAs/InGaAsP single quantum well laser emitting at 1.03 μm[1]. On the other hand, (411)A-oriented GaAs substrates have been used to form extremely flat hetero-interfaces over a large area (1 cm x 1 cm) in GaAs/AlGaAs quantum wells (QWs) grown by MBE[2,3]. In this paper, we report for the first time that extremely flat interfaces are formed in InGaAs/AlGaAs QWs grown on (411)A-oriented InGaAs ternary substrates by MBE.

$In_{0.04}Ga_{0.96}As/Al_{0.3}Ga_{0.7}As$ QWs with well widths of L_W= 1.2, 2.4, 3.6, 4.8, 7.2, 12 nm on an $In_{0.04}Ga_{0.96}As$ (50 nm)/$Al_{0.3}Ga_{0.7}As$ (10 nm) buffer layer (290 nm in total) were grown on (411)A and (100) $In_{0.04}Ga_{0.96}A$ sabstrates simultaneously at 520 C by MBE. Growth rates were 1.0 μm/h (GaAs), 0.43 μm/h (AlAs) and 0.04 μm/h (InAs). V/III ratio was 7 - 10 (in pressure). Figure 1 shows a photoluminescence (PL) spectrum from the QWs on the (411)A substrate at 4.2K. Very sharp 6 peaks from the 6 QWs are observed in addition to one peak (853 nm) from $In_{0.04}Ga_{0.96}As$ in the buffer layer. A peak at 687 nm with full-width-at-half-maximum (FWHM) of 9.0 meV comes from the QW of L_W=1.2 nm, and a peak at 734 nm with FWHM= 6.6 meV comes from the QW of L_W=2.4 nm, and so on. Figure 2 shows FWHMs of the PL peaks for $In_{0.04}Ga_{0.96}As/Al_{0.3}Ga_{0.7}As$ QWs grown on (411)A and (100) $In_{0.04}Ga_{0.96}As$ substrates as a function of wavelength. FWHMs of the (411)A QWs are almost 40% smaller than those of (100) QWs for shorter wavelengths, implying that very flat interfaces are realized in $In_{0.04}Ga_{0.96}As/Al_{0.3}Ga_{0.7}As$ QWs grown on the (411)A $In_{0.04}Ga_{0.96}As$ substrate.

Figure 1

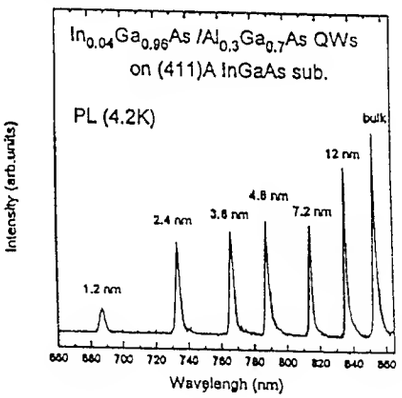
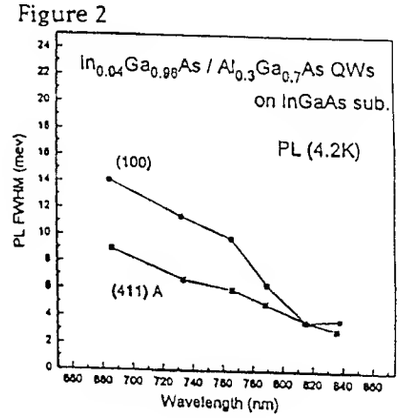


Figure 2



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DETAILED BALANCE BETWEEN IMPACT IONIZATION AND AUGER RECOMBINATION OF TRIONS IN PHOTOEXCITED GaAs/AlAs QUANTUM WELLS

A.Manassen, E.Cohen, Arza Ron, E.Linder and L.N. Pfeiffer*
Solid State Institute, Technion - Israel Institute of Technology, Haifa 32000, Israel.
*AT&T Bell Laboratories, Murray Hill, NJ 07974, USA

Fax. no: 972-4-235107, e-mail: phr80ma@ssrc.technion.ac.il

We studied the photoluminescence (PL) spectra of the (e1:hh1)1S exciton (X) and its negatively charged trion (X^-=(X,e)) in photoexcited GaAs/AlAs quantum wells (QW) in the temperature range $2<T<30K$. We utilize the properties of undoped, mixed type I - type II QW's in order to generate a long lived 2DEG in its wide ($L_W=198\text{Å}$) GaAs wells and a separate 2DHG in its narrow ($L_N=26\text{Å}$) wells. The samples are photoexcited by two cw lasers with energies $E_{L1}\sim(e1-hh1)_W$ (the wide wells bandgap) and $E_{L2}\geq(e1-hh1)_N$ (that of the narrow wells). We control the 2DEG density ($0\leq n_e\leq 10^{11}cm^{-2}$) by the L2 laser intensity ($I_{L2}\propto 10^{-3}I_{L1}$). The PL spectrum of the wide well is dominated by the X and X^- lines. Both electrons and trions show cyclotron resonance peaks from which it can be deduced that they are free. We measured the intensity ratio ($\frac{I_{X^-}}{I_X}$) as a function of temperature and I_{L2} and from it we obtain the ratio $R=\frac{n_{X^-}}{n_X}$ between the trion and exciton populations. We find that up to T=14K the system of 2DEG, X and X^- is in equilibrium and R is well fitted by a two level model using the 2DEG chemical potential. Qualitatively this means that R is an increasing function of n_e and a decreasing function of T. Above T=14K, namely, $k_BT>E_{X^-}$ (the trion binding energy), and in the range $10^9<n_e<10^{10}$, R decreases with n_e while for $n_e>10^{10}$ it again increases as n_e increases. The dependence in the low density range is explained by e-X^- impact ionization. For the higher n_e range, a mechanism of trion formation with a higher rate than the impact ionization is apparently effective. We propose a process of Auger recombination in which two electrons and an exciton interact. One electron binds to the exciton and the other takes up the excess momentum. This process rate is $A(T)n_Xn_e^2$ while the impact ionization rate is $B(T)n_{X^-}n_e$. As n_e increases, a detailed balance is expected between these two processes leading to $\frac{n_en_X}{n_{X^-}}=\frac{B(T)}{A(T)}$. It is observed experimentally that this population ratio indeed approaches a constant value for $n_e\geq 2\times10^{10}cm^2$.

BISTABILITY AND QUANTISATION OF CONTINUUM STATES IN PIEZO-ELECTRIC QUANTUM WELLS

L R Wilson, D J Mowbray, M S Skolnick, D W Peggs, G J Rees[a], R Grey[a], G Hill[a] and M A Pate[a].

Department of Physics, University of Sheffield, Sheffield S3 7RH, UK

[a]Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S1 4DU, UK

We report optically induced bistability and quantisation of continuum states in the electrical and optical characteristics of piezo-electric (pz) strained (111)B $In_{0.15}Ga_{0.85}As$-GaAs single quantum wells (QWs). The two effects do not occur in (100)-grown QWs and are a direct consequence of the large pz fields of ~$2x10^5$ V/cm in such (111)B structures. The QWs are incorporated in the i-regions of p-i-n junctions. The bistability is observed as a region of hysteresis in the low temperature I-V characteristics of the device under illumination. Depending on the sweep direction, for a given voltage the device is stable in one of two states corresponding to either low or high photocurrent.

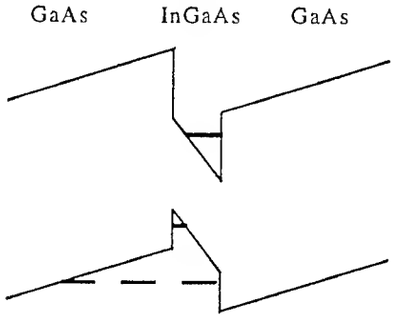

Figure 1. Band-profile of a piezo-electric single QW p-i-n structure.

We demonstrate that the bistability arises due to photo-induced charge build-up in the QW. As shown in Fig 1, the effective barrier on the low potential side of the QW is increased relative to a (100) structure resulting in a decreased tunnelling probability, and enhanced charge build-up in the QW. As the sample is swept towards reverse bias, the charge build-up increases until the self-consistent potential can no longer support further increase of the charge in the well; the carriers are then ejected from the QW, and the device switches to the high current state. Low temperature PL spectra obtained with the sample in the two photocurrent states confirm this model. A clear increase of linewidth in the low relative to the high photocurrent state is observed due to electron band-filling of n_s=$4x10^{11}cm^{-2}$ in the low photocurrent state. Self-consistent Poisson-Schrodinger simulations of the structure with n_s=$4x10^{11}cm^{-2}$ show that this value of charge density agrees very well with the band profile necessary to maintain the structure in the low photocurrent state at this bias. Further increase of reverse bias leads to increased tunnelling out of the well and switching to the high current state.

Secondly we report the observation of above barrier continuum transitions in the photocurrent (pc) spectra of the QW. As can be seen from Fig 1, due to the form of the band edge profile arising from the pz field, continuum states are quasi-bound in the (111)B strained QWs (dashed level in the valence band well). We have observed clear features in pc spectra arising from such above barrier states, with energies as a function of bias in very good agreement with our calculations.

Stimulated Emission in $Zn_{1-x}Cd_xSe/ZnSe$ quantum wells: Exciton, biexciton and free-carrier recombinations

L. Calcagnile, D. Greco, G. Coli' and R. Cingolani

Istituto Nazionale di Fisica della Materia-Dipartimento di Scienza dei Materiali, Universita' di Lecce, via Arnesano, I-73100 Lecce

M. Lomascolo and M. Di Dio

Centro Nazionale Ricerca e Sviluppo Materiali (PASTIS-CNRSM), SS 7 Appia Km 713 , I-72100 Brindisi, Italy

L. Sorba and A. Franciosi

Laboratorio Tecnologie Avanzate Superfici e Catalisi del Consorzio Interuniversitario di Fisica della Materia, Area di Ricerca, Padriciano 99, I-34012 Trieste

Although $Zn_{1-x}Cd_xSe/ZnSe$ multiple quantum well structures have been extensively studied in the last years because their applications in the field of electronic and optoelectronic devices, many fundamental issues have not yet been clarified. For instance the understanding of the physical process responsible for stimulated emission is still under investigation. Certainly, the exciton binding energy and the oscillator strength are higher in II-VI materials with respect to III-V so that excitons can really play an important role in the lasing process, even at room temperature and at high excitation density. On the other hand above the Mott threshold free-carrier recombination occurs. In this work we investigated the role of excitons and free-carriers in the lasing process in a variety of experimental conditions. $Zn_{1-x}Cd_xSe/ZnSe$ multiple quantum well structures were grown by molecular beam epitaxy with x in the range from 0.10 to 0.26 and well width from 3 to 20 nm. We performed the optical characterization of the samples by photoluminescence, magnetoluminescence, time-resolved photoluminescence measurements as a function of the excitation power density. In the samples with $x \approx 0.10$ and at relatively low incident power densities, we observed different radiative recombination channels involving excitons which dissociates into free-carriers at higher intensities, whereas in the samples with $x \approx 0.26$ the stimulated emission originates from localized excitons. An estimate of the density of localization centers is also given based on time-resolved luminescence measurements. In extremely good samples biexciton recombination is also observed, red-shifted $\approx$ 10 meV from the main excitonic peak. A Phase diagram model involving free-excitons and free-carriers according to a self-consistent many-body renormalized mass action law, is found to describe our experimental results. Localized excitons or biexcitons can be involved in the recombination processes depending on the actual degree of disorder due to compositional and structural fluctuations. Our work allows to give a clear and definitive picture of all the processes involved in the radiative recombinations in II-VI materials. Consequently, from our results many information about the optimization of $Zn_{1-x}Cd_xSe/ZnSe$ quantum well laser structures can also be obtained.

ROLE OF LOCALIZED EXCITONS IN THE STIMULATED EMISSION IN ULTRA THIN CDSE/ZNSE/ZNSSE SINGLE QUANTUM WELL STRUCTURES

Shigeo Yamaguchi, Hitoshi Kurusu, Yoichi Kawakami,
Shizuo Fujita and Shigeo Fujita

Department of Electronic Science and Engineering,
Kyoto University, Kyoto 606-01, Japan

Currently, exciton-related lasing mechanism has attracted much interest in II-VI semiconductors in terms of the potential for achieving the low lasing-threshold. In particular, localized excitons have intensively been studied in II-VI quantum well (QW) structures with alloy well layers (ZnCdSe or ZnCdS) because the optical gain can be easily reached due to their low density tail states. Biexcitons have also been reported to play an important role in lasing in ZnCdSe/ZnSe[1] QW structures. Moreover, recent theoretical calculation has predicted that the biexcitons have to be localized in deep potential minima in order that they can contribute to the optical gain even at room temperature[2]. In this papar we report the lasing mechanism in strained CdSe QWs with different monolayer (ML) thickness, where both excitons and biexcitons are highly localized due to the interface roughness and the fluctuation of well width between CdSe and ZnSe layers.

The sample structure grown by MBE on (100) oriented GaAs substrate is as follows : a 0.85 μm $ZnS_{0.07}Se_{0.93}$ cladding layer was deposited, following a 30nm ZnSe buffer layer. The well layer, a CdSe single QW, was sandwitched between ZnSe waveguide layers (500nm in each), followed by a 0.15μm $ZnS_{0.07}Se_{0.93}$ capped layer.

In order to study the recombination dynamics, the time-resolved photoluminescence (TR-PL) has been detected from the sample surface. For photo-pumped lasing experiments, the emissions were monitored from the cleaved facet with the length of resonator being approximately 1mm. The TR-PL of the 1-ML CdSe QW structure has revealed that localized biexctions emission appears at 2.6767eV at 20K which is located on the low-energy side of the main peak (2.6897eV) if the excitation power density is raised above $3\mu J/cm^2$. Photo-pumped lasing emission is also observed at 2.6780 eV, indicating that localized biexcitons may relate to the formation of optical gain.

We will focus on the dependence of the degree of exciton localization and temprature on the lasing mechanism.

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papers per title

Quasiparticle lifetime in a two dimensional electron system in the limit of low temperature and excitation energy

D. Menashe and B. Laikhtman

Racah Institute of Physics, Hebrew University, Jerusalem 91904, Israel

We study theoretically the quasiparticle lifetime, due to Coulomb scattering, in a two dimensional electron system. It has long been established that in the limit of low excitation energy and temperature, the inverse lifetime behaves as $\tau_{ee}^{-1}(\mathrm{p}) \propto (\Delta/\epsilon_F)^2 \ln(\epsilon_F/\Delta)$ where $\Delta \equiv \max(|\epsilon_\mathrm{p} - \epsilon_F|, k_B T)$. This result has been obtained in the leading order of the Coulomb interaction. We show that higher order terms in the interaction contribute higher order logarithmic factor, meaning that a correct theory must sum up all orders of the interaction. After performing this summation, using the Keldysh diagram technique, we find that the renormalized lifetime still has the same general form as above. On the other hand we find that only forward scattering contributes to the lifetime, whereas in leading order theory, both forward and backward scattering make a contribution (a similar result has already been obtained for the 2D Hubbard model). This leads to a different proportionality constant for the lifetime. Because we employ the Keldysh diagram technique, we are also able to give an expression for the collision operator in the Boltzmann equation, which can be used in the study of near equilibrium processes.

Longitudinal magneto-resistance of superlattices caused by barrier inhomogeneity.

D. L. Miller and B. Laikhtman

Racah Institute of Physics, Hebrew University, Jerusalem, 91904,Israel

Abstract

It is known that classical magneto-resistance along the direction of the magnetic field is zero if this direction is a symmetry axis. On the other hand experiments in superlattices give a nonzero magneto-resistance when both the current and the magnetic field are in the growth direction. This magneto-resistance can be explain by inhomogeneities of the superlattice barriers. The general problem of the magneto-resistance of the inhomogeneous media can not be solved analytically. In the present work we solve this problem for the superlattices. assuming that fluctuations are small. We find that the result depends very significantly on the correlation length of the fluctuations. We also find that the fluctuations of the electron potential are not uniform along the superlattice and depend on the superlattice length.

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Effects of a periodic magnetic field on magnetotransport in a quantum wire

Zhen-Li Ji and D. W. L. Sprung

Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4M1 Canada

We have investigated the transport properties of a quantum wire in the presence of a perpendicular magnetic field. A finite section of length L is subject to a periodically varying magnetic field,

$$\mathbf{B} = \left\{ B_0 + B_m \sin\left[\frac{m\pi}{L}\left(x + \frac{L}{2}\right)\right]\right\}\hat{\mathbf{z}} \qquad -\frac{L}{2} < x < \frac{L}{2}.$$

Here $m = 1, 2, \ldots$ is an integer oscillation index of the magnetic field, and B_m denotes the field modulation amplitude. B_0 is an uniform background field, applied to the entire sample. The quantum wire has infinite length in the x direction and is confined laterally by hard wall potentials at $y = -W/2$ and $W/2$. Inside the channel the potential is taken to be zero. We used a finite element method [1] for the calculations.

Our study focuses on the effects on electron transport of magnetic field profile, the maximum field strength, and thickness of the magnetic barriers. We find that there are dips in conductance just below each mode threshold. As the field modulation amplitude B_m or length L is increased, these conductance dips broaden and the dips for higher modes become more pronounced. However, their positions change little.

We also varied the number of periods of the field modulation, for fixed L. Electronic transport is affected in a pronounced way by such changes. In general, transmission along the wire is enhanced by magnetic fields with periodic profile. Increasing the number of periods of the modulation can lead to a reopening of the channel, as the field strength is increased.

To examine further the role of the magnetic field in transmission, individual transmission coefficients for different modes in the leads are studied. The transmission coefficients for different incoming modes are quite different in magnitude. However, the positions of the transmission peaks and dips for individual propagating modes are almost the same at larger values of the field modulation amplitude B_m in our model. Finally the possibility of measuring these conductance dips and channel reopenings in present day semiconductor structures is discussed.

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Microstructure and photoluminescence mechanism of porous silicon

Hyek Bok Rhee and Gil Yong Chung

Samsung Display Devices, Display R&D center, Suwon, Korea

The recent discovery that highly porous silicon (PS) can efficiently emit visible at room temperature has drawn a great deal of attention mainly due to the potential applications in realizing all Si-based optoelectronics and display devices. In this paper, we have studied microstructure of PS by SEM and AFM and crystallinity of that by RAMAN and thin film XRD at various anodic etching condition. Also we have studied photoluminescence and surface state of PS by FT-IR and XPS to find origin of visible light of PS.

PS was formed by anodization of 5 - 35 Ωcm, boron-doped, (100) silicon in a anodizing cell containing hydrofluoric acid (HF) electrolyte. Electrical contact was made to the back side of the wafer using Al film about 1 μm and Pt counter electrode. The distance of Si wafer and Pt was 4 cm. HF electrolyte concentration varied from 1 to 0.1 comparing to ethanol volume with current flow from 10mA to 100mA.

At lower anodizing state, SEM analysis shows that the surface structure of the PS is similar to a condensed state of nanometer order Si microcrystals. The size of Si microcrystals is in the range of 10 - 30 nm and cross-sectional SEM shows PS layer has different two structure such as surface film region and macroporous region. Macroporous region shows 2 - 3 μm pore and 6 μm thickness. At higher anodizing state, PS structure shows only macroporous region. RAMAN spectra shows a peak due to the Si-Si vibration mode of crystalline silicon at 521 cm^{-1} and there is no peak corresponding to amorphous silicon at 480 cm^{-1}. Photoluminescence spectra shows two peaks regardless of anodizing condition. The wavelength of major peak in PL increases with increasing anodization current and intensity of that decreases with increasing anodizing time at constant HF concentration. However minor peak in PL shows constant wavelength about 600 nm and intensity regardless of anodizing condition.

Surface vibrational modes and reflection times of phonons in finite-size superlattices

Seiji Mizuno and Shin-ichiro Tamura,

Dep. of Applied Physics, Hokkaido University, Sapporo 060, JAPAN

We theoretically study the reflection times of acoustic phonons injected from a substrate to a finite-thick superlattice (SL) with a free surface. The time needed for phonons to complete a reflection process is given by the derivative of the phase of the reflected amplitude with respect to frequency. We calculate this "phase time" and find a large enhancement when the frequency of the injected phonons coincides with an eigenfrequency of the surface vibrations in the SL. This large time delay is due to the resonant interaction between the bulk and surface phonons in SL's. In fact, we can derive a Breit-Wigner form for the expression of the reflection time around the resonant frequency. Numerical simulations for the time evolution of phonon packets reveal interesting features characteristic of this resonant interaction. Our results suggest that time-resolved phonon reflection experiments should provide important information on the surface vibrations in SL's.

CHARACTERIZATION OF CdTe/MnTe SHORT PERIOD SUPERLATTICES BY X-RAY DIFFRACTION AND RAMAN SCATTERING

E.Dynowska[1], W.Szuszkiewicz[1], M.Jouanne[2], G.Karczewski[1], J.Kossut[1]

[1] Institute of Physics Polish Academy of Siences, Warsaw, Poland
[2] Laboratoire de Physique des Solides, Universite Paris VI, France

$(CdTe)_{12}/(MnTe)_n$ superlattices (SLs) with n = 2, 4, or 8 were grown by the MBE on (001) GaAs SI substrates misoriented of 2° towards the next (110). SLs with 200 periods were grown on a 3 μm thick CdTe (001) buffer layer, their thickness varied between 0.9 and 1.3 μm.

For the structural characterization of SLs X-ray diffraction studies were applied. There is about 2.3% lattice mismatch between MnTe and CdTe layers. Parallel ($a_{\parallel}$) and perpendicular ($a_{\perp}$) lattice parameters were measured by Bond's four-crystal method. Reciprocal space mapping using high-resolution diffractometer was also performed. The strain parameters γ for investigated SLs were determined by these methods.

Raman spectra were measured both at room temperature and at about 15 K using 514.5 nm Ar^+ laser excitation line. Folded LA phonons were observed at room temperature, a few first doublets for these phonons are well seen. An effect of a change in the frequencies of LA phonons due to strain arising from the lattice mismatch was estimated and discussed. The strain gave also rise to the shift in the optical phonon frequencies. A linear-chain model was applied to describe the behaviour of observed confined LO phonons. A possible influence of the Mn diffusion (resulting in a non abrupt distribution of Mn atoms close to the interface) on the Raman scattering data was analyzed.

The shape of the scattering background observed in Raman spectra at low temperature suggests the presence of amorphous Te precipitations in SLs, resulting probably from high values of the Te/Mn flux ratio during crystal growth.

Nonequilibrium Phonon Drag Effects on Hot Electron Thermoelectric Power in Semiconductor Quantum Wells

M.W. Wu and W. Sun

Department of Physics, University of Science and Technology of China, 96 Jingzhai Road, Hefei, Anhui, 230026, China
Department of Physics and Engineering Physics, Stevens Institute of Technology, Hoboken, New Jersey 07030, U.S.A.

N.J.M. Horing and H.L. Cui

Department of Physics and Engineering Physics, Stevens Institute of Technology, Hoboken, New Jersey 07030, U.S.A.

E-Mail: mwu@phdec2.phy.stevens-tech.edu Fax: (201)216-5638

We employ a balance equation formulation to examine the effects of phonon drag on hot electron thermoelectric power in semiconductor quantum wells in the nonlinear regime. In this, we incorporate the role of the finite phonon relaxation time due to phonon-phonon interactions with its full complement of temperature-, wavevector- and mode-dependencies. Our treatment of thermoelectric power is based on extension of the nonlinear balance equation approach to a weakly inhomogeneous quantum well in the presence of a temperature gradient and an electric field, both in the plane of the quantum well. Earlier nonlinear works have emphasized the role of the diffusion part of thermoelectric power, neglecting the phonon drag contribution. However, phonon drag is known to be very important in linear transport for both bulk and 2D semiconductor systems. In fact, it is usually so large that the diffusion contribution would not be discernible unless measurements were extended to very high or very low temperatures. In this paper we clarify the importance of the phonon drag contribution to thermoelectric power of quantum wells in the nonlinear regime, under hot-electron transport conditions and with careful treatment of the phonon relaxation time dependencies, which have been successful in producing agreement with experimental data over a broad range of densities and temperatures in the linear regime. Our nonlinear hot electron quantum well transport analysis shows that for intermediate electric field strength, and/or for high impurity concentrations (for which the electron drift velocity is lower than the sound velocity), the role of phonon drag in thermoelectric power is markedly enhanced at low lattice temperatures.

INTERSUBBAND FAR INFRARED ABSORPTION AND SPONTANEOUS EMISSION BY HOT HOLES IN MULTIPLE QUANTUM WELLS

L.E.Vorobjev, D.V.Donetsky, E.A.Zibik, L.E.Golub*,

V.Ya.Aleshkin**, L.K.Orlov**, O.A.Kuznetsov**

St.Petersburg State Technical University, St.Petersburg

*Ioffe Physico-Technical Institute, St.Petersburg

**Institute for Microstructure Physics, N.Novgorod

The spontaneous emission and absorption in the wavelength range $\lambda = 80...300$ μm in the multiple quantum well structures $GaAs/Al_{0.5}Ga_{0.5}As$ and $Ge/Ge_{0.93}Si_{0.07}$ caused by direct intersubband transitions of hot quasi-two-dimensional holes were investigated. The hole heating was provided by the pulse electric field applied along the layers.

The peaks in emission spectra associated with singularities of joint density of states for some pairs of subbands were observed. A comparison between the experimental and theoretical emission spectra for $GaAs/Al_{0.5}Ga_{0.5}As$ structures has been conducted. A correlation between the peculiarities in emission spectra and results of calculation of dispersion curves taking into account the lattice deformation for $Ge/Ge_{0.93}Si_{0.07}$ structure was discussed. A good agreement has been achieved.

The hot hole temperature was obtained comparing hot and equilibrium hole light absorption.

The work was supported by Russian Foundation for Basic Research.

EXCITONIC RECOMBINATION EFFECTS ON LOW TEMPERATURE PHOTOCURRENT SPECTRA OF GaAs/AlAs SUPERLATTICE P-I-N DIODES

K.Fujiwara, K.Kawashima, K.Kawasaki, K.Tominaga# and M.Hosoda#
Kyushu Institute of Technology, Tobata, Kitakyushu 804, Japan
#ATR Optical and Radio Commun. Res. Lab., Seikacho, Kyoto 619-02, Japan

Recent investigations[1-3] of the perpendicular transport of photoexcited carriers within the intrinsic quantum-wells or superlattice layer of a p-i-n diode reveal that, in order to make the photocurrent spectral lineshape faithfully reflect the electroabsorption features, the transit times of carriers through the intrinsic region must be shorter than the carrier recombination time. Otherwise, the photocurrent spectra show sever distortion. Previously, two mechanisms are proposed for the transit time effects, the above-barrier carrier drift model at room temperature[1] and the dominant electron tunneling model at 6 K[3] to exploit variations of the effective recombination length by the applied axial electric field.

In this paper photocurrent (PC) spectra of GaAs/AlAs superlattice p-i-n diodes with relatively thick barrier thicknesses are investigated as a function of applied electric field at 300 K and 15 K. While the 300 K PC spectra always show positive peaks corresponding to confined exciton resonances in absorption spectra due to efficient exciton thermal dissociation, a definitive dip (negative peak) is observed within the low temperature positive PC signals under the nearly flat-band conditions. It is found that this dip exactly coincides in energy with the 1S heavy-hole exciton resonance absorption peak, which is confirmed by photoluminescence excitation (PLE) spectra measurements, and that the normal positive excitonic PC peak is regained with increasing the field strength. These results provide direct evidence for the importance of excitonic recombination channels for shortening the carrier recombination time, which strongly decreases with reducing the lattice temperature[4]. That is, the PC signal due to excitonic absorption is efficiently quenched by the same excitonic radiative recombinations at lower temperatures. With increasing the field the tunneling escape time becomes short and can be comparable to or smaller than the recombination time. Thus, a photocurrent model is given to explain temperature-dependent PC intensity variations with the field, which takes the competition between the excitonic recombination and the tunneling escape times into account.

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Surface plasmons in interaction with quantum well inter- and intra- subband plasmons

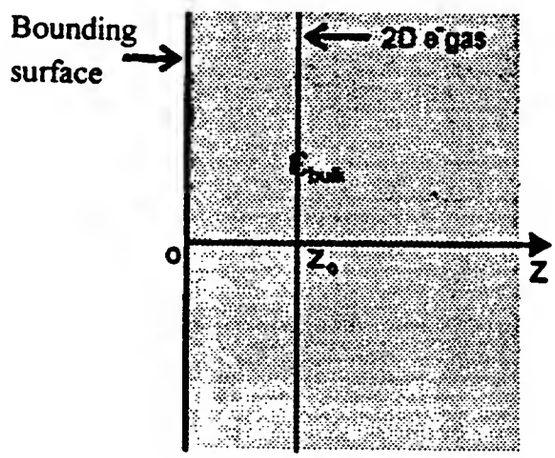
Norman J. Morgenstern Horing

Department of Physics and Engineering Physics, Stevens Institute of Technology

Hoboken, New Jersey 07030, U.S.A.

E-Mail: n1horing@stevens-tech.edu Fax: (201)216-5638

The coupled mode spectrum of a bounded, semi-infinite plasma in which a 2D quantum well is embedded is examined here. The 2D electron quantum well is parallel to, and at a distance z_0 from the bounding surface of the semi-infinite host plasma, which has dielectric function $\epsilon_{bulk}(\omega)$ (see figure below). We analyze the collective modes of this combined system, including the coupling and hybridization of the surface and bulk plasmons of the host medium with the inter- and intra- subband plasmons of the nonlocal, dynamic quantum well. Our formulation of the random phase approximation (RPA) coupled mode dispersion relation is based on an explicit closed form inversion of the spatially inhomogeneous, nonlocal, dynamic dielectric function of the combined system which we carry out directly in position representation, and an examination of its frequency poles. (This explicit result can also supply the relative excitation amplitudes of the coupled modes as the residues at the frequency poles.) In addition to hybridizations that involve modes of the host medium with those of the quantum well which do not depend on z_0, we find coupled collective modes which do depend on the separation of the quantum well from the bounding surface, involving both intersubband and intrasubband plasmons jointly with the host surface and bulk modes.



Surface electromagnetic waves in dielectric arrays of 1D and 2D periodicity

F. Ramos-Mendieta* and Peter Halevi‡

*Centro de Investigación en Física, Universidad de Sonora

Apdo. Post. 5-088, Hermosillo, Sonora 83190, México.

‡Insituto Nacional de Astrofisica, Optica y Electrónica

Apdo. Post. 51, Puebla, Puebla 72000, México.

Abstract

Under suitable conditions surface electromagnetic waves can propagate parallel to the surface of a photonic band-gap material. Inside the periodic structure the field decays because of interference effects. On the air side the decay occurs because the propagation wavevectors of these waves are larger than the vacuum wavevector ω/c. We have studied the TE and TM surface wave properties for both dielectric superlattices and 2D photonic crystals. For both cases we find the dispersion curves $\omega(\kappa)$ strongly dependent on the position of the surface (the cut-plane of the infinite structure). In 1D the TM modes are affected by the Brewster effect in an important way. The selected 2D array consists of parallel cylinders having square-cross section and forming a square lattice. The cut-plane is perpendicular to the [10] crystal direction. If the infinite 2D array gives rise to a complete band-gap (for waves propagating in the plane of periodicity) we find surface (Bloch) modes only for cut-planes through a cylinder layer, thus leaving a truncated cylinder layer at the surface. On the other hand, in the presence of incomplete band-gaps surface modes can also occur. In these conditions the waves exhibit an upper limit of the propagation wavevector (the lower limit is given by the air light-line). When this upper limit is given by a bulk band, there are no surface modes for a complete cylinder layer at the surface. On the other hand, when the upper limit is determined by a point of crossing of neighboring bands, we find surface modes even for a complete cylinder layer at the surface.

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Highly Sensitive 2DEG Hall Arrays

V. Cambel, P. Eliáš, R. Kúdela, B. Olejniková, M. Ďurica, and J. Novák
Institute of Electrical Engineering, Slovak Academy of Sciences, Dúbravská cesta 9, 842 39 Bratislava, Slovakia

ABSTRACT:

Monolithically integrated and highly sensitive Hall sensor arrays made of a modulation-doped heterostructure (based on InGaP/InGaAs and InGaAs/InP systems) have been investigated. The smallest array realized consists of 8 in-line sensors of a 2μm x 2μm active area with a 4μm separation. To our knowledge, this is the smallest area of a Hall array sensor ever published (up to now 3.5μm x 3.5μm, see Ref. 1, 2). The sensor is developed for experiments in which the magnetic field of high temperature and standard superconductors is probed [1-3]. To allow direct contact with a sample tested, the active area of the array is formed on the top of a MESA structure.

The realization of single and multiple quantum wells selectively delta-doped in the barrier material enhanced the mobility in the quantum well and the sensitivity of the probe in comparison with a standard epitaxial Hall GaAs device. A physical model of the structure including a self-consistent description of coupled Schroedinger and Poisson equations have been solved to better understand the influence of the heterostructure design on its electronic properties. A final vertical structure was designed according to these theoretical calculations.

Decreasing the dimensions of the Hall sensor array brings about a problem of inhomogeneity of residual voltages of the individual probes. This is due to an uncertainty of final dimensions of the device details. Special electronics have been developed to compensate for these residual voltage inhomogeneities. The compensation enhances the dynamic range of the device and allows us to measure DC magnetic fields in the range 5 μT - 10 T.

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An investigation of envelope function methods using pseudopotential calculations for InAs/AlSb heterostructures

R.A.Coles, S.Brand and R.A.Abram
Department of Physics, University of Durham,
Durham DH1 3LE, UK

Envelope function theories have been widely used in the calculation of the electronic states of semiconductor heterostructures, and especially in models of semiconductor devices. Envelope functions are an essential feature of simple effective mass and **k.p** models, but a concern in recent years has been the precise form of the interface boundary conditions to be applied at abrupt heterojunctions. That problem has been resolved by Burt[1], who has developed a rigorous theoretical framework for the envelope function approach and shown how appropriate boundary conditions can be determined from an approximation to the exact Schrödinger equation. The restriction of the Fourier expansion of the envelope functions to a particular Brillouin zone allows unique envelope functions to be defined (for a given basis set, such as the zone centre states). These functions and their spatial derivatives are then continuous on the microscopic scale across abrupt heterostructure interfaces, unlike those in the usual effective mass and **k.p** calculations, which have a discontinuity in the spatial derivative. Here the predictions of Burt's formal theory are tested on a real system. In particular, this paper shows how envelope functions may be derived from the results of pseudopotential calculations, and investigates the properties of these functions in various models and approximations. The system considered is a (100) InAs/AlSb quantum well, which has received sparse attention compared to GaAs/AlGaAs and other systems but has a number of promising device applications. The numerical problems associated with deriving envelope functions and performing calculations for this system are highlighted and comparisons to standard envelope function methods are made.

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Band offsets in $In_{0.15}$ Ga $_{0.85}As/GaAs$ and in $In_{0.15}$ Ga $_{0.85}As/Al_{0.15}Ga_{0.85}As$ studied by photoluminescence and cathodoluminescence

E.M. Goldys[1], H.Y. Zuo[1], M.R. Phillips[2], C.M. Contessa[2], T.L. Tansley[1]

1 Semiconductor Science and Technology Laboratories, Macquarie University, North Ryde, 2109 NSW, Australia

2 Microstructural Analysis Unit, University of Technology, Sydney, 2007 NSW, Australia

Strained quantum wells (QWs) stimulate considerable interest due to an increased flexibility available for band-gap engineering. Accurate predictions of confined state energy levels are based on the detailed knowledge of a number of parameters, and, in particular, on the valence and conduction band offsets, often expressed as the band offset ratio $Q = \frac{\Delta E_c}{\Delta E_g}$ where E_c is the conduction band offset and ΔE_g is the bandgap difference. We present results of low temperature photoluminescence and cathodoluminescence measurements of strained undoped $In_{0.15}$ Ga $_{0.85}As/GaAs$ and in $In_{0.15}$ Ga $_{0.85}As/Al_{0.15}Ga_{0.85}As$ quantum wells. The spectra show evidence of several emission lines including the first electron-first heavy hole (1e-1hh) and first electron-first light hole (1e-1lh) excitonic transitions. While in both structures the 1e-1hh transition is always direct, opinions found in the literature on the direct/indirect character of the 1e-1lh transition are divided. Our measurements allow us to address this issue by the comparison of the experimentally derived value of the 1hh-1lh hole confined state separation (with excitonic effects taken into account) with the calculated values for a wide range of band offset ratios Q. The calculations were performed within the eight band effective mass aproximation, where the action Lagrangian was set up and subsequently solved using the finite element method. The accuracy of the relevant parameters other than Q and, in particular, the effect of the well thickness and composition inaccuracy, was carefully considered. We calculated energies of direct (type I) and indirect (type II) transitions, that coexist for certain band offset ratios, while for smaller valence band offsets (larger Q) only type II transitions for light holes are possible as there is no confined light hole state for very small band offsets. The comparison of the calculated and the observed energies leads us to conclude, that while for $In_{0.15}$ Ga $_{0.85}As/GaAs$ both type I and type II light hole transition are possible, in the case of $In_{0.15}$ Ga $_{0.85}As/Al_{0.15}Ga_{0.85}As$ the data are consistent with type II alignment only. The 1hh-1lh energy difference and the emission energies corrected for excitonic effects allow to deduce the value of the band offset ratio Q for $In_{0.15}$ Ga $_{0.85}As/Al_{0.15}Ga_{0.85}As$ to be 0.85.

ON THE THEORY OF THE ENERGETIC SPECTRUM OF LATERAL SUPERLATTICES (LSL) ON VICINAL PLANES: THE ROLE OF CRYSTAL POTENTIAL

V.A.PETROV

Institute of Radio Engineering and Electronics
Russian Academy of Sciences,Mokhovaya 11,Moscou,103907,Russia
E-mail:L193@ire.rc.ac.ru Fax:(095)203-84-14

As is known,the existence of superlattice effects in quantum wells (QW) on vicinal planes predicted (V.A.Petrov, 1977) and discovered independently in 1977 (T.Cole,A.Lakhani,P.J.Stiles) initiated with the appearance in these systems of a new cristallographic translation period in the plane of quantum wells A >>a (a - lattice constance).The emergence in these LSL of the periodic system of atomic steps allows to explain the appearance of minigaps (MG) in the energetic spectrum of particles in QWs by the scattering of electrons on such steps. At the same time it is evident that the contribution to the MG formation should also be made by all crystallographic planes in the area of localization of the particle wave function.

This paper theoretically shows that the consideration of only crystal potential and of the potential locating the particle in LSL on vicinal planes results in the appearance of MG even without taking into account of the step structure of the QW boundarys. A method has been developed that makes it possible to calculate the energetic spectrum of these systems for the arbitrary localizing potential by leaving the effective mass approximation in single-valley semiconductors of the GaAs type. For the cases of the rectangular QW and inversion layer analitical expressions have been obtained for MG magnitudes which depend on the parameters of the crystal and localizing potentials as well as on angles that define the orientation of the QW planes in the crystal. It has been shown that for LSL of the GaAs type the magnitudes of MGs approximate several meV.

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ELECTRON STATE SYMMETRIES AND OPTICAL TRANSITIONS IN $(GaAs)_m(AlAs)_n$ SUPERLATTICES

P. TRONC, Yu. E. KITAEV* and A.G. PANFILOV*
Ecole Supérieure de Physique et Chimie Industrielles,
10 rue Vauquelin, 75005 PARIS, France

and

R.A. EVARESTOV
St Petersburg State University,
Universitetskaya nab. 7/9, 199034 St. Petersburg, Russia

The electron structure of superlattices is generally studied within the envelope function approximation. This approximation cannot grasp the full symmetry group of the atomic arrangement. This point is particularly important in the case of superlattices made of two stochiometric compounds. They can indeed be considered as a new class of artificially grown crystals.
Using the method of induced band representations of space groups[1], a new method which drastically reduces the length of the calculations, we have performed a complete group-theory analysis of electron state symmetries in $(GaAs)_m(AlAs)_n$ superlattices grown along the [001], [110] and [111] directions. The spin-orbit interaction has been taken into account. The formulae giving, for arbitrary numbers of monolayers m and n, the arrangements of atoms over the Wyckoff positions have been obtained. The selection rules for both direct and phonon-assisted optical transitions have been derived. Using the results of the group-theory analysis, we predict some variations in the optical transitions when m and/or n are varied. We also propose polarized-light optical experiments to establish the detailed electron-band structures of the superlattices. This could help in particular to decide among the numerous and sometimes contradictory results of the various electronic-structure calculations which have appeared in the literature for the superlattices grown along the [001] directions.

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* Permanent address : A.F. Ioffe Physical-Technical Institute, Politekhnicheskaya 26, 194021 St. Petersburg, Russia.

SWITCHING BETWEEN BISTABLE CURRENT STATES IN HYSTERESIS LOOPS IN WEAKLY COUPLED SUPERLATTICES $GaAs/Al_xGa_{1-x}As$ (x=0.3).

Rasulova G.K., Efimov Yu.A., Murzin V.N.
P.N.Lebedev Physical Institute RAS, 117924 Leninsky prosp.53, Moscow, Russia.

Current voltage characteristics of 30 periods 390A GaAs/110A $Al_xGa_{1-x}As$ superlattices (SL) are studied. Due to wide size of quantum well's (QW), six subband levels are determined. Rich structure with series of negative differential conductivity (NDC) oscillations with five hysteresis loops due to considerable current bistability (current drops in sweep-down direction relative to sweep-up in two times) are observed. Each hysteresis loop corresponds to certain type of resonant alignment between different subband levels in neighbouring QW's, the number of oscillations is comparable to the number of periods in the SL, the voltage period of these oscillations is equal to energetic spacing between subband levels /1/.

Switching effect between bistable current states by applying rectangular voltage pulse in any point of each hysteresis loops are observed for the first time. Time of switching is about 1 mks. Switching goes with fixed pulse polarity and threshold pulse amplitude. Switching effect are explained by shrinkage and expansion of the domain boundary size. Changes of the domain boundary size are evaluated from static IV characteristics. Switching effect are considered as a particular case of temporal current oscillations, which have been observed in weakly coupled SL's /2/.

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GIANT HIGH-FIELD DOMAIN CURRENT HYSTERESIS AND QUENCHING EFFECT IN LOW-DOPED LONG PERIOD GaAs/AlGaAs SUPERLATTICES

Yu.A.Efimov, Yu.A.Mityagin, V.N.Murzin

P.N.Lebedev Physical Institute, Leninsky pr., 53, 117924, Moscow, Russia

The dominant mode of weakly coupled superlattice (SL) quantum well structure is sequential resonant tunneling that results in electric field domain (EFD) formation and negative differential conductivity (NDC) behaviour if the SL's are sufficiently doped or optically excited /1/. We present here the first experimental and theoretical investigation of the phenomena in low-doped long period SL, which include the consideration of the resonant tunneling problem in depend on the impurity concentration, as well as the experimental results revealing the profound high-field domain current hysteresis and distinctly expressed multistability effects due to well defined resonance properties of low-doped SL.

The theoretical numerical simulation results based on extended microscopic model /2/ for a case of SL with several subbands taking into account carrier injection demonstrate the effect of EFD boundary broading as well as the effect of current hysteresis decreasing and quenching in SL at low doping level. The impurity threshold criterium of EFD formation in SL is formulated as a cooperative result of both of these phenomena, caused by limitation of current and increase of mismatching of resonant subbands at the domain boundary region.

The experimental results of vertical transport in SL (GaAs/AlGaAs, $d_w = 350A$, d_b = 120 A, N = 30) are presented which exhibit pronounced step-like I-V characteristics with several (up to 6) plateau regions (belong to different subband type of domains) and related series of oscillatory-like NDC resonances caused by the shift of the domain boundary over the SL. A suitable choice of SL parameters as well as the doping level /3/ allowed to achive a strong hysteresis - a sweep-up I-V curve revealed more than 2 times higher plateau current values than the sweep-down one . A set of multiple stable branches inside the hysteresis regions (up to N-1) arising from different locations of the domain boundary along the SL was observed. The overlapping of the branches results in the existance up to 8 stable current values (multistability) for a given value of applied voltage, so the SL behaves as a multistable device.

Using the tunneling probability effective curve as a fitting parameter the experimental proof of the validity of the model used is obtained that gives a satisfactory explanation of the main features of the measured current-voltage characteristics. As a result of experimental and theoretical study the evidence of significantly "nonresonant" electric domain structure is obtained revealing that while most of SL is coupled resonantly in low-field domain region (at sweep-up hysteresis current branch) the coupling of subbands in low- field domain region (at sweep-down hysteresis current branch) and mainly in high-field domain region (at the both of the hysteresis current branches) principally deviates from resonant. The current through the SL is limited by tunneling at the domain boundary, which is actually "nonresonant" and is accompanied by increasing of subbands misalignment in low doped SL.

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NEW RELAXATION EFFECTS IN TWO-DIMENSIONAL CONDUCTING SYSTEMS

R.N.Gurzhi, A.N.Kalinenko, A.I.Kopeliovich

B.Verkin Inst. for Low Temp.Phys. & Engn. 47 Lenin Ave., Kharkov, Ukraine

The Coulomb interaction in two-dimensional ($2D$) case forms a peculiar liquid of electrons the kinetic properties of which are determined by collisions of electrons having opposite momenta [1,2]. The new hydrodynamic-type effect due to the properties of such liquid was observed in experiments on electric conductivity of high-mobility $2DEG$ wire [3]. The Poisseuille flow of electron liquid along the wire is impossible if $d \ll \sqrt{\tau_a \tau_\varepsilon} v_F$, where d is the width of wire; τ_a, τ_ε are the relaxation times of odd- and even in momentum distributions, respectively, $\tau_a \gg \tau_\varepsilon$; v_F is the Fermi velocity. The reason is that the drift electron distribution has no time to be form for the time of diffusive reaching of an electron to the wire boundary. In this case the motion of carriers to the boundary is the quasi-1D diffusion. As a result of collision with an equilibrium electron of opposite momentum, the initial nonequilibrium electron turns into a nonequilibrium hole moving in the opposite direction, and, vice versa. (By a "hole" we mean the absence of an electron under the Fermi level.) The electric conductivity is determined by carriers moving at small angles α to the boundary [1], as the time of diffusive reaching of the boundary $(d^2/(v_F\alpha)^2\tau_\varepsilon$ is large for them.

It is best to observe unusual properties of $2D$ electron liquid in experiments on evolution of electron beams injected into $2DEG$. A direct registration of a hole component of the beam, which is formed for the time of the order τ_ε after injection, is feasible. One can analyze the regularities of 1D-diffusion of carriers, the influence of a weak magnetic field which makes diffusion two-dimensional, and relatively slow time broadening of a beam according the law $t^{1/4}$ due to electron-electron collision [2]. We have shown that reflection of holes from boundary, where injector is placed, weakens essentially the beam injecting perpendicularly to the boundary. But if the injection is inclined, the situation changes radically . Specular reflection forms two beams in which normal components of current are opposite, and current density not only does not decrease but increases with time (at $t \gg \tau_\varepsilon$).

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ELECTRON BEAMS INJECTED INTO 2DEG AS A WAY TO STUDYING ELECTRON-ELECTRON RELAXATION PHENOMENA

A.I.Kopeliovich,
B.Verkin Institute For Low Temp.Phys. & Engn.
47, Lenin Ave., Kharkov 310164, Ukraine

The decrease of dimensionality of a conducting system from three tc two changes qualitatively mechanisms of momentum (angular) relaxatior related to electron-electron collisions [1]. The observation of the evolutior of electron beams injected into 2DEG under the effect of collisions [2] may turn out a most promising method of the experimental investigation of specific two-dimensional relaxation mechanisms. In this case a problem of obtaining of sufficiently narrow beams becomes actual.

The quantization of a conductance of a point contact, the width of which d is a smooth function of a coordinate along a channel ($d_{min} \ll R$, R is the radius of channel curvature) was considered in [3]. The present work is dedicated to a analysis of angular distribution of electrons which have passed through a contact in the same "adiabatic" model of a contact. It is shown that the characteristic angular width of a beam $\delta\varphi \simeq (d_{min}/R)^{1/3}$. At these angles between electron velocity and a contact axis an adiabatic approach becomes not valid, i.e. it is impossible to separate the description into a quantum-mechanical problem on transverse motion and quasi-classical one on longitudinal motion. The effective length of a channel for passing electrons appears to be of the order of $d_{min}^{1/3} R^{2/3}$ that allows one not to use extra long channels. The oscillating dependence of beam density on the angle with a period $\simeq \delta\varphi$ has been obtained. The similar oscillations were observed experimentally [2].

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Superlattices in the presence of strong external AC electric fields: frequency commensurability effects in dressed minibands

P. H. Rivera, M. A. Andrade Neto, R. Rey-Gonzalez and P. A. Schulz

Instituto de Física Gleb Wataghin C. P. 6165 Unicamp 13083-970 Campinas SP Brasil

The behaviour of electrons in semiconductor heterostructures, interacting with strong external AC fields, has been a subject of growing interest in the past few years. Recent developments in fabrication of semiconductor microstructures and tunable far-infrared lasers led to a new field of investigation, relating Quantum Optics and Solid State Physics. One of the striking predictions is the collapse of superlattice minibands[1], as well as resonant tunneling suppression[2] for certain intensities of external ac fields. The evolution of dressed electronic states, starting from bare electronic states, gives rise to Brillouin Zones of quasienergies[1]. In the present work we describe an electronic miniband with a tight-binding model. The interaction with a laser field of a given frequency is described by a time-independent Hamiltonian which replaces the semiclassical time-dependent Hamiltonian[3]. The eigenvalues form a field-intensity dependent quasienergies spectrum. We extend the interaction to a simultaneous second strong external AC field. A time independent Hamiltonian can be obtained if the frequencies of both fields are commensurate. The quasienergies spectrum show self-similar properties resembling Hofstadter-like spectra. The possibility of experimental observation of these effects is also discussed.

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Transition from 3-Dimensional to 2-Dimensional magneto-excitons

Ivan F. Costa, José A. Brum

IFGW- DFESCM, Universidade Estadual de Campinas, 13081-970 Campinas (SP), Brazil

The optical transitions in direct gap semiconductors are dominated by the excitonic states. These effects are even more pronounced in low-dimensional semiconductors. In the 3-dimensional (3D) limit, the electron and hole are strongly correlated in all directions; but the two body exciton problem, taking into account Coulomb interaction, can still be described in terms of uncorrelated relative and center-of-mass motions. On the other hand, for a strongly confined quantum well (QW), the carriers kinetics along the growth direction is determined by the barrier potential and a quasi 2-dimensional (2D) description is well suited to describe the excitonic states. An interesting situation arises for large QW widths or shallow QW barriers when the confinement potential and the Coulomb interaction are of the same order (M. Fritze et al., Phys. Rev. Lett. **76**, 106 (1996)).

We present the results of the calculation of the exciton states in these situations for the GaAs-(Ga,Al)As system. A center-of-mass quantization of the 3D exciton is used to describe the effects of the QW barriers. As the quantum well width decreases or depth increases, the breaking of translational invariance leads to 2D-like exciton. In this case, the exciton wave function under goes a deformation and the relative motion mixes with the center-of-mass motion. We also consider the presence of an external magnetic field applied parallel and perpendicular to the growth direction. In the former, the magnetic field effects do not couple directly with the confined direction. The main effect of the magnetic field is then to modify the 3D exciton size and it can be used to monitor the transition from 3D to 2D systems and its effects on the exciton states. In the later configuration, the magnetic field induces an extra coupling between the center-of-mass and the relative motions.

Another important characteristic of quasi-2D systems is the coupling among the heavy- and light-hole excitons. A bulk valence mass is a good approximation for the 3D limit. For 2D systems, the mass reversal dominates the in-plane kinetics. We are in an intermediate situation and the importance of taking into account the hole mixing depends on the combination of several parameters as the barrier width/height and the strength of the magnetic field.

We study the exciton states focusing on the mixing of the relative and center-of-mass motion and the heavy- and light-holes mixing for various well widths and intensity of magnetic field, from very shallow to deep quantum wells, to visualize the change of dimensionality of the system. Our results are in good agreement with the available experimental results.

EVIDENCE OF INTERFACE ROUGHNESS IN RESONANT TUNNELING STRUCTURES

Y. Galvão Gobato [1], A.L.C. Triques [1], P.H. Rivera [1], P.A. Schulz [1]

M. Maialle [2], B. Vinter [3], Y. Guldner [4]

(1)Departamento de Física do Estado Sólido e Ciência dos Materiais, IFGW-UNICAMP, CP 6165, Campinas-SP, 13083-970, Brazil.

(2) Departamento de Física Geral e Aplicada, Universidade São Francisco, Rua Alexandre Rodrigues Barbosa,45, 13251-900,- Itatiba, Brazil

(3) Laboratoire Central de Recherches, Thomson CFS 91404 Orsay Cedex,France

(4)Laboratoire de Physique de la Matière Condensée, Ecole Normale Supérieure, 24, rue Lhomond, 75005 Paris, France.

We report on photoluminescence (PL) and photoluminescence excitation (PLE) measurements in GaAs/InGaAs/AlAs double barrier structures. A splitting in the quantum well photoluminescence spectra with an energy separation of 8 meV is observed. This splitting corresponds roughly to changes in the transition energy due to a monolayer variation in the QW and evidences interface roughness and island formation in the quantum well. The intensity, position and halfwidth of these lines are investigated as a function of applied bias in order to change the density and distribution of electron and holes in the QW. The experimental results support the interpretation of line splitting due to interface roughness and island formation. The bias polarity dependence of PL lines are consistent with the asymmetry in the I(V) characteristic, i.e., whether the inverted interface is at the emitter or collector barrier. The temperature dependence of the PL intensities shows that transfer of carriers between islands can be tuned with applied bias and that states in differents islands are selectively populated with eletrons via resonant tunneling.

Electron Capture in Quantum Wells via Electron-Electron Scattering with Exchange and via Electron-Hole Scattering

K. Kálna and M. Moško
Institute of Electrical Engineering, Slovak Academy of Sciences
Dúbravská cesta 9, Sk-842 39 Bratislava, Slovakia

The electron capture in a quantum well plays an important role in optimizing the performance of semiconductor quantum well (QW) lasers. In this work we analyze the electron capture in the $Al_xGa_{1-x}As/GaAs/Al_xGa_{1-x}As$ QW with 500-Å $Al_xGa_{1-x}As$ barriers, embedded between two thick $AlAs$ layers. Using the "Fermi golden rule" approach [1] we calculate the electron capture times due to electron-electron (e-e), electron-heavy hole (e-h) and electron-polar optic phonon (e-pop) scattering. Capture times oscillate as function of QW width with nearly the same period, but with very different amplitude.

For an electron (hole) density of $10^{11}cm^{-2}$ in the QW the e-e (e-h) capture time is $10^1 - 10^3$ times larger than the e-pop capture time except for QW widths near resonance minima. Near the resonances it is only $2 - 3$ times larger and at high enough carrier densities even smaller than the e-pop capture time. Thus the capture efficiency of the QW with optimized (resonant) width can be further optimized by varying the carrier density. *Compared to the e-e capture, the e-h capture time shows a more complicated oscillatory structure. The effect of exchange on the e-e capture process is analyzed and found to enhance the e-e capture time twice.*

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Electron effective mass determination in asymmetric modulation-doped field-effect transistor heterostructures using $In_xGa_{1-x}As$ quantum well and $(InAs)_n(GaAs)_m$ superlattice channels

L.A.Cury[♣], J.Beerens[‡], F.M.Matinaga[♣], S.L.S.Freire[♣], M.A.Py[†], M.V.B. Moreira[♣]
[♣] Departamento de Física - Instituto de Ciências Exatas - Universidade Federal de Minas Gerais, Caixa Postal 702, 30161-970 Belo Horizonte, Minas Gerais, Brazil
[‡] Centre de Recherche en Physique du Solide et Département de Physique - Université de Sherbrooke, Sherbrooke, Québec, Canada J1K 2R1
[†] Institute for Micro- and Optoelectronics, Swiss Federal Institute of Technology, CH - 1015, Lausanne, Switzerland

Modulation-doped field-effect transistor heterostructures have been investigated by cyclotron resonance (CR) and low temperature photoluminescence (PL). Two types of samples were studied, which consisted, respectively, of an $In_xGa_{1-x}As$ quantum well (QW) channel, and a $(InAs)_n(GaAs)_m$ short period superlattice (SL) channel sandwiched between $Al_{0.3}Ga_{0.7}As$ and GaAs layers.

The high quality of the samples was confirmed by the width of CR and PL peaks. A comparison of the results obtained on both types of samples showed that the optical and transport properties of SL-channel heterostructures are similar or better than those of heterostructures based on a $In_xGa_{1-x}As$ QW channel.

CR absorption measurements were performed at 4.3K using far-infrared laser line wavelengths of 96.5μm, 118.9μm and 163.0μm. The CR spectra showed the expected Ando oscillations[(1)], from which we could determine the 2DEG concentration, and also the filling factor at a given magnetic field. The knowledge of the filling factor is essential for the quantitative analysis of the CR data, since CR involves electronic states close to the Fermi level, which is relatively high in our samples. This brings about important non-parabolic corrections that have to be taken into account in the comparison of the measured cyclotron mass with theory. In our model we first determined the electron wavefunction $\Psi(Z)$ using a self-consistent method. Then we obtained the effective mass at the Fermi level by integrating $\Psi^2(Z)/m^*(Z)$ over the whole structure, taking into account non-parabolic effects. Band-gap values were obtained from the PL measurements.

Our results show a significant enhancement of the electron effective mass in the heterostructures, as compared to what is reported in the literature for bulk $In_xGa_{1-x}As$[(2)]. For a given electron concentration and well thickness, this enhancement is still stronger in the heterostructures based on SL channel. The main advantages in growing $(InAs)_n(GaAs)_m$ superlattices to simulate $In_xGa_{1-x}As$ quantum wells will be discussed, based on a comparative analysis of our results obtained for the two different series of samples.

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MoD Transport and localization in 2-D systems

Compressibility measurements of two-dimensional electron gases

N. K. Patel‡, I. S. Millard†, C. Foden‡, E. H. Linfield†, M. Y. Simmons†, D. A. Ritchie†, and M. Pepper†‡

† Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 OHE, U.K.

‡ Toshiba Cambridge Research Centre, 260 Science Park, Milton Road, Cambridge CB4 4WE, U.K.

Double quantum well structures have been used to study the compressibility of a two-dimensional electron gas (2DEG). The electron gases are formed in two GaAs quantum wells separated by a thin AlGaAs or AlAs barrier, where measurements of the carrier density changes in the lower layer are used to obtain information on the compressibility of the top 2DEG. By depleting the upper 2DEG with a surface gate bias, the compressibility is shown to change from positive at high 2DEG carrier densities to negative at low densities. This may be explained by considering the relative changes of the kinetic, Hartree and many-body interaction contributions to the 2DEG compressibility. At high 2DEG carrier densities the positive kinetic term dominates whilst at low densities, the negative contributions due to interactions and Hartree band bending dominate. Studies of a wide range of structures has enabled the effects of 2DEG separation, well width and effective mass to be analysed. Comparison with a model which solves the Poisson and Schrödinger equations in a self-consistent manner provides good qualitative agreement for all the parameters. These calculations show that the Hartree contribution is significant and explains the large discrepancy between the experimental results and analytical calculations, where the Hartree term is not included.

Capacitance Spectroscopy of Compressible and Incompressible Stripes in a Narrow Electron Channel.

D. Schmerek[a,d], S. Manus[a], A.O. Govorov[b], W. Hansen[a,d], J.P. Kotthaus[a], M. Holland[c]

[a]Sektion Physik, Ludwig-Maximilians-Universität, Geschwister-Scholl-Pl. 1, 80539 München, Germany

[b]Institute of Semiconductor Physics, 630090, Novosibirsk, Russia.

[c]Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G128QQ, U. K.

We study the capacitance of a single narrow (300 nm) electron wire at high quantizing magnetic fields. We demonstrate that capacitance spectroscopy allows us to study directly compressible and incompressible liquids in an electron channel. The electron wire is field-induced in a metal-insulator-semiconductor heterostructure beneath a center electrode that is located between a tuning-fork shaped electrode. The electrostatic potential defining the wire edge is controlled by the voltage between the center electrode and the fork shaped electrode. The experimental results are well described by a simple model considering the formation of compressible and incompressible stripes in the electron channel [1,2]. In high magnetic fields the capacitance is expected to be proportional to the surface area of the compressible stripes [2]. The capacitance spectra demonstrate an asymmetry of the capacitance minimum at filling factor $\nu=2$. The model predicts such an asymmetry to be the specific feature of compressible and incompressible stripes, which are established by electron-electron interaction. Therefore the mechanism causing the capacitance minimum in our experiment is principally different to that of a two-dimensional system [3], where the minimum is symmetrical and reflects the defect-induced density of states. In addition, the present experiment allows us to avoid effects caused by in-plane lateral currents. This is an essential advantage in comparison with experiments on two-dimensional electron channels with current contacts [4].

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[d]present and permanent address: Institut für Angewandte Physik, Universität Hamburg, Jungiusstr. 11, D-20355 Hamburg

THE INTERPLAY OF THE PERIODIC POTENTIAL AND ELECTRON-ELECTRON SCATTERING IN SURFACE SUPERLATTICES

A. Messica, U. Meirav, Ady Stern, Hadas Shtrikman, V. Umansky, and D. Mahalu

Weizmann Institute of Science, Rehovot 76100, Israel
Fax: +972 8 9344128, Tel. +972 8 9342519, e-mail: hmeirav@wis.weizmann.ac.il

We study transport in short surface superlattices (SSLs), which are realized by a grating array of Schottky gates on a high-mobility two-dimensional electron gas (2DEG). We measure the differential conductance $G \equiv dI/dV_{ds}$, as a function of drain source voltage, V_{ds}. Substantial suppression of G – up to 80 percent – is found when the drain source electric field is increased. This phenomenon is remarkable in that it occurs on a very small scale of V_{ds}, corresponding to electric fields of a few volts/cm. Temperature dependence is equally interesting: we find an order of magnitude *increase* in resistance with T which is quadratic in the range of $T < 10$ K.

Two pictures are considered in the interpretation of these observations. The first relies solely on the formation of Bloch minibands by the SSL periodic potential. Within this picture the nonlinear *I-V* characteristic is due to the onset of Wannier Stark localization. A priori this is a plausible explanation in light of the quantities involved, including spatial period of the SSL, the field scale, and the low scattering rate of these 2DEGs. The temperature dependence would then be attributed to thermal saturation of miniband transport.

An alternative picture further considers the role of *e-e* scattering. While in a uniform 2DEG *e-e* scattering has only *in*direct influence on the resistance, we argue that in a SSL there is a direct contribution of *e-e* scattering to the resistance, which stems from the loss of translational invariance and the formation of minibands. Since the *e-e* scattering rate is approximately quadratic in T, the resulting resistance is also quadratic in T. In this picture the suppression of conductance at moderate V_{ds} results from an increase in *e-e* scattering due to the excess kinetic energy imparted to the carriers by the electric field. The observed quadratic T-dependence supports the idea that *e-e* scattering plays an important role in the resistance of SSLs.

We note that within either interpretation, these observations are seen as a novel manifestation of miniband formation in SSLs.

Spin-Dependent Hole Delocalization Enhancement by Bandfilling Effects in Degenerate Asymmetric Double Quantum Wells

M. Kemerink[1], P.M. Koenraad[1], P.C.M. Christianen[2], A.K. Geim[2], J.C.Maan[2], J.H. Wolter[1], and M. Henini[3]

[1] *COBRA Interuniversity Research Institute, Eindhoven University of Technology, P.O.Box 513, 5600 MB Eindhoven, The Netherlands.*
[2] *High-Field Magnet Laboratory, Toernooiveld, 6525 ED Nijmegen, The Netherlands.*
[3] *Department of Physics, University of Nottingham, Nottingham NG7 2RD, U.K.*

Abstract

The Asymmetric Double Quantum Well (ADQW) has been intensively studied in the past few years. This interest is motivated by the promising possibilities for device applications, as well as by the novel physics of these structures. One of the most interesting features is the different leakage of hole wavefunctions of different magnetic moment, leading to a *macroscopic* separation of 'spin-up' and 'spin-down' states, even when there is no resonance between levels in the left and right well. This effect was coined 'Spin-Dependent Hole Delocalization'.

Hole and electron dispersion relations and wavefunctions are obtained as exact Eigenfunctions and Eigenvalues of the full 4*4 Luttinger Hamiltonian. The wavefunctions and the electrostatic potential are calculated self-consistently. From a comparison of calculations with both Shubnikov-de Haas and Photo-Luminescence Excitation experiments it is shown that self-consistency is essential to explain most experimental results quantitatively and as we point out, even qualitatively.

Furthermore, we will show that the SDHD is strongly enhanced when self-consistency is included. Of the two underlaying mechanisms, the charge induced extra asymmetry in the confining potential and the smaller energy gap between the lowest heavy-hole levels, it is shown that the latter is by far the most important. Since no direct coupling between heavy-hole states is present, the interaction has to take place through light-hole states. This is confirmed by calculations on shallow wells, where the light-holes are not or weakly bound. For these structures the SDHD-enhancement was found to be absent. As a result of the gained insight, the macroscopic separation between spin-up and -down states can be tailored in a wide range of values, by choosing appropriate doping concentrations and barrier heights.

Nonlinear impurity screening and metal insulator transition in strongly depleted 2D electron gases

K. Schrüfer, C. Metzner*, M.Ch. Hofmann and G.H. Döhler
Institut für Technische Physik I, Universität Erlangen, Erwin-Rommel-Str. 1, Germany
* University of Tokyo, RCAST, 4-6-1 Komaba, Meguro-ku, Tokyo 153, Japan

In high mobility modulation δ-doped hetero-structures the scattering of the electrons in the 2D gas by the charged impurities is supressed by introducing a thick spacer layer. With decreasing spacer layer thickness d, however, the lateral (parallel to the layers) variation $\Delta n^{(2)}(\mathbf{r})$ of the electron density profile $n^{(2)}(\mathbf{r}) = \overline{n}^{(2)} + \Delta n^{(2)}(\mathbf{r})$ due to the impurity induced potential fluctuations becomes more and more pronounced. If the electrons in the conducting channel are depleted to an average density $\overline{n}^{(2)}$ sufficiently below the 2D doping concentration $n_D^{(2)}$, the lateral density fluctuations become comparable to $\overline{n}^{(2)}$. A further depletion $\overline{n}^{(2)} < \overline{n}_{MIT}^{(2)}$ causes a metal insulator transition (MIT), where the electron profile $n^{(2)}(\mathbf{r})$ even disintegrates into a set of spatially insulated clusters, separated from each other by potential barriers that exceed the Fermi level Φ. This interesting phase of a strongly disordered interacting electron system has, to our knowledge, not yet been investigated adequately. In this regime, a detailed analysis of the 2D spatial structure of the electron density profile is of fundamental importance for understanding the optical and transport properties of the system.

A two-dimensional selfconsistent calculation of the lateral conduction band $V(\mathbf{r})$ and electron density profile $n^{(2)}(\mathbf{r})$ has been performed using 4 different theoretical approaches. To investigate the importance of quantum effects we start with a full-scale 2D Hartree calculation and compare the results to a non-linearized 2D version of the semiclassical Thomas-Fermi approximation. Surprisingly good agreement is found for the effective selfconsistent potential profiles and density of states over a broad range of electron densities $\overline{n}^{(2)}$.

For the high- and low-density limits, we apply additionally the random phase approximation (RPA) and a modified version of an algorithm (BEGS [1]) known from the theory of impurity bands for weakly doped systems. We demonstrate that the linear RPA approximates the Hartree results for a high average electron density, but fails to describe the strongly perturbated electron gas. The latter regime, however, can be well described by the BEGS algorithm.

Finally, we investigate the density-induced MIT as a classical percolation problem for the spatial regions of zero and finite electron density. From the simulations we can extract the critical percolation density $\overline{n}_{MIT}^{(2)}$ and also the heights and widths of the potential barriers separating the metallic droplets, which are essential for calculating transport properties like activation energies and tunneling rates in the insulating regime.

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Transport properties of a high mobility electron gas formed in a $Ga_{0.25}In_{0.75}As$/InP quantum well containing line dislocations.

P. Ramvall, N. Carlsson, P. Omling, L. Samuelson, and W. Seifert
Department of Solid State Physics, Lund University
Box 118, S-221 00 Lund, Sweden.

We present transport measurements on a modulation-doped (Si), 90-Å-thick $Ga_{0.25}In_{0.75}As$/InP pseudomorphic quantum wells (QW). The structures were grown on a (001) InP substrate by low pressure metal organic vapor phase epitaxy. A typical mobility for the electrons in the two dimensional electron gas (2DEG) of this type of structure is $\mu = 500000$ cm^2/Vs giving a mean free path of about 6.5 μm. Line dislocations are formed in the $Ga_{0.25}In_{0.75}As$ when the critical thickness is exceeded. The length of the dislocations (<-110> direction) varies between 20 μm and 100 μm and the shortest distance (<110> direction) between two dislocation lines is 1 μm. The measurements revealed a large negative magnetoresistance in the longitudinal resistance at low magnetic fields for transport perpendicular to the dislocation lines. A similar effect has been observed for a strong *periodic* potential imposed upon a 2DEG in a AlGaAs/GaAs heterojunction.[1] We attribute the negative magnetoresistance to come from electrons on open orbits experiencing scattering against the potential created by the dislocation lines. This effect disappears when all electrons perform closed cyclotron orbits (magnetic breakdown), in agreement with measurements. In order to convincingly show that the observed effects come from the random potential created by the line dislocations, 150 nm wide trenches with the same distribution as the dislocation lines were etched on the surface of samples with no dislocations in the QW. Two different series were fabricated: One with a strong potential, i.e., the modulation potential is comparable to the Fermi energy of the 2DEG, where the modulation doped layer was completely etched away and one with a weak potential where just one third of the doped layer was removed. The longitudinal resistance for the strong potential exhibits a strong negative magnetoresistance while the weak potential gives rise to a positive magnetoresistance, in agreement with Ref. 1. This result verifies our statement that the dislocation lines introduce a strong potential in the 2DEG.

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Spatial Correlation Effects of Charged Impurities on Electron Mobility in δ-doped GaAs

J.M. Shi,[*,#] *P.M. Koenraad,*[#] *A.F.W. van de Stadt,*[#]
F.M. Peeters,[*] *J.T. Devreese,*[*,#] *and J.H. Wolter*[#]

*Departement Natuurkunde, Universiteit Antwerpen (UIA), B-2610 Antwerpen
#Departement Natuurkunde, Technische Universiteit Eindhoven, NL-5600 Eindhoven

We present a theoretical study of correlation effects of charged impurities on electronic properties of highly (Si) δ-doped GaAs. In such a system several electronic subbands are populated, and at low temperature ionized impurity scattering is the most important scattering mechanism. Increasing doping density and/or applying a hydrostatic pressure increases the population of the DX state. which is helpful to show these correlation effects in the system.

Much experimental work has been done on δ-doped semiconductors in the presence of external pressure in order to observe the effects due to DX centers However, only a few number of theoretical studies have included spatial correlations in their calculation. Using the widely accepted d^+/DX^- model, we have described the measured results deduced from Shubnikov-de Haas measurement by Skuras *et al.* [1] for the population and the quantum mobility of electrons in different subbands. A reasonable agreement between theory and experiment is reached for pressures not in access of 10 kbar.

By approximating the pair correlation functions of the charge distribution in two dimensions by step functions, the equilibrium equation of the reservoirs of filled DX centers and the quasi-two-dimensional electron gas are solved self-consistently. This gives the electron density of the subbands which were found to be in excellent agreement with the experimental findings [1]. The DX energy and its derivative with respect to pressure were determined to be 290 meV and -9 meV/kbar, respectively, which are consistent with the values reported in literature [2].

The influence of the correlations of the charged impurities on the electron mobility is taken into account by the structure factor of the charge distribution in the δ-layer. This factor is determined by the Fourier transformation of the pair correlation functions. By comparing the measured quantum mobility [1] to theoretical results obtained with three different methods: (1) no correlation effects [3], (2) in the step-function approximation, and (3) Monte Carlo simulations of the charge distribution. we have found that the theoretical analysis underestimates the electron mobility systematically in the models (1) and (2), while model (3) gives an excellent agreement for the lowest subband, and a qualitative behavior but twice as large as the experimental data for the excited subbands.

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Free Electron Laser Saturation Spectroscopy of Neutral Donors and Negative Donor Ions Confined in GaAs/AlGaAs Quantum Wells

S.R. Ryu, G. Herold, J. Kono, M. Salib, B.D. McCombe --- *SUNY at Buffalo, Buffalo, NY 14260*

J. Kaminski, S.J. Allen, Jr --- *CFELS, UC Santa Barbara, Santa Barbara, CA 93106*

We have performed a series of magneto-transmission and magneto-photoconductivity measurements on two donor (Si)-doped GaAs/$Al_{0.3}Ga_{0.7}As$ multiple-quantum-well samples (well width 200Å) as a function of power density with the UCSB Free Electron Laser (FEL) over a wide range of laser power under steady state conditions in fields up to 8T (sample 1 : $2\times10^{10}cm^{-2}$ (well center); sample 2 : 2×10^{10} / 4×10^{10} cm^{-2} (well center / barrier centers)). Saturation of the D^0 1s-$2p^-$ transition, the D^--singlet transition and CR was observed. From analysis of the D^0 1s-$2p^-$ data in sample 1, effective lifetimes were found to vary systematically with laser frequency, decreasing from 62 ns ± 20 ns at 84 cm^{-1} ($2p^-$ state below the N=0 L.L) to 3 ns ± 0.7 ns at 124 cm^{-1} ($2p^+$ state above the lowest L.L.). This behavior is very similar to that of the D^0 1s-$2p^+$ transition of uncompensated bulk GaAs. The initial appearance and increase of CR in the same sample is due to the (non-resonant) impact ionization of donors by the strong electric field of the incident laser beam. CR starts to saturate as the electron density in the N=1 L.L. increases at higher laser powers. Unusual behavior was observed for the saturation of the D^--singlet transition in sample 2; i.e., the absorption coefficient initially increased by up to 40% and then showed complete quenching at higher laser powers, very different from the neutral donor results. Photoconductivity measurements of the D^0 1s-$2p^+$ transition were also carried out for sample 1 at the same time (*in situ*) as the transmission, and show rather different behavior than transmission; i.e., even though transmission data show complete quenching, the photoconductivity measurements still show non-negligible transition strength. Photoconductivity measurements probe only pure absorption, while transmission probe net absorption; i.e., the net results of the difference between the pure absorption process and the stimulated emission process. Therefore, at high incident laser intensity, the two measurements give complementary results.

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Tuesday

TuA Tunneling in quantum dots

Self-organized growth of quantum dot-tunnel barrier systems

M. Dilger, K. Eberl, R. J. Haug, and K. von Klitzing

Max-Planck-Institut für Festkörperforschung, Heisenbergstr. 1, 70569 Stuttgart, Germany

Direct epitaxial growth on patterned substrates has been used to fabricate complete single-electron transistor devices in a single growth step [1,2]. The new fabrication scheme allows the realization of two electrical leads - drain and source - which are separately connected to a self-assembled quantum dot via self-aligned tunnelling barriers. This allows the investigation of single-electron transport through the self-assembled quantum dot. The potential of the self-assembled quantum dot can be tuned by a voltage on a in-plane gate, also realized by direct epitaxial growth. This allows the investigation of the Coulomb-Blockade effect in the direct grown devices.

The pre-patterning of the substrate consists of a bow-tie shaped ridge, fabricated by reactive-ion etching of a GaAs-substrate using Si_xN_y as mask material. The surface selectivity of the epitaxial growth rates leads to a modulation of the thickness of the deposited $Al_{0.33}Ga_{0.67}As/GaAs$ heterostructure. In particular, the modulation of the GaAs-quantum well causes the formation of the single-electron transistor.

The facet formation during the direct growth is characterised using scanning-electron microscopy. The modulation of the epitaxial layer is confirmed using atomic-force microscopy. Transport measurements reveal that the Coulomb-Blockade in the direct grown structures is visible up to temperatures of T=6 K. Spectroscopic transport measurements at T=22 mK with finite source-drain voltages allow the determination of the charging energy and the characterization of the tunnelling barriers.

As the fabricated single-electron transistor devices can be tuned by applying a voltage to only a single gate, more complex or even integrated single-electron circuits can be realized with this simple new fabrication scheme.

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Modelling of inter-dot Coulomb interaction effects in field-effect transistors with embedded quantum dot layer

C. Metzner, G. Yusa and H. Sakaki
University of Tokyo, RCAST, 4-6-1 Komaba, Meguro-ku, Tokyo 153, Japan

Recent progress in semiconductor technology enables the fabrication of novel heterostructures [1], where a layer of InAs quantum dots, formed by the Stransky-Krastanov growth mode, is embedded into the depletion zone between the conducting channel and the gate electrode of a modulation doped GaAs/n-AlGaAs field-effect transistor. By varying the gate voltage, a controllable amount of electrons can be trapped within the dot-layer, leading to characteristic changes of the band profile within the heterostructure. This manifests as a shift of the gate threshold voltage in a Hall effect measurement of the channel electron concentration as a function of gate-source voltage.

These history dependent changes of the electrical device characteristic are modelled by a selfconsistent calculation of the band structure, including in detail the Coulomb interaction between the charged quantum dots. In the region of moderate gate voltages, where the leak current between the 2D channel and the gate is still weak, a good agreement with the experiment is found.

The probability distributions of the energies of charged and neutral dots are analyzed for different degrees of dot layer occupation. Similar to the case of 2D impurity bands, the inter-dot Coulomb repulsion leads to correlation effects in the spatial pattern of charged dots and influences the position of the Fermi level relative to the average conduction band edge at the dot layer. However, due to the neutrality of unoccupied dots and the very long trapping life time, unique differences are found in this system. The effects of a possible occupation of the quantum dots with two electrons as well as the consequences of the additional energy disorder due to dot size fluctuations are discussed. Additionally, the possibility of observing the inter-dot correlations in a future optical spectroscopy study complementary to the electrical measurements is critically investigated.

Finally, dynamical aspects of an electron current flowing through a layer of partially charged traps are analyzed with respect to the hysteresis effects found experimentally at high gate voltages.

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RANDOM TELEGRAPH SIGNAL IN TUNNELING TRANSPORT THROUGH A SINGLE 0-D IMPURITY STATE

M. R. Deshpande, R. G. Wheeler, M. A. Reed
Physics Department; Yale University, P. O. Box 208120, New Haven, CT 06520
R. J. Matyi
Texas Instruments Incorporated, Dallas, TX 75265

The experimental realization of granular electronic systems, such as low dimensional semiconductor and ultra small metallic systems, has generated much research activity in the field of single electron tunneling. We present here the first observation of Random Telegraph Signal (RTS) in tunneling transport through a single electron channel.

Isolated donor impurities in the quantum well regions of large area resonant tunneling heterostructures form localized (~ 10 nm) 0-D states, similar to fabricated quantum dot states[1,2]. At an applied bias where one such state aligns with the emitter Fermi level, a new channel is opened for electron tunneling and the dc current through the device exhibits a step-like increase. We report the first observation of RTS occurring during transport through these discrete single channels. At a given bias, random switching between two current levels is observed as a function of time. Switching is observed only in narrow bias regions near the edges of the current steps (i.e. near the Fermi level in the emitter) but not on the current steps themselves. Such switching is not observed for all impurity tunneling steps, but is observed for more than one impurity and in both forward and reverse bias. In a magnetic field the switching signal is observed to track with the dc current step edges, which exhibit diamagnetic shifts, thus proving unambiguously that this signal is intimately related to the single electron tunneling channels. The magnitude of these discrete current jumps is observed to increase dramatically by an order of magnitude as the temperature is lowered from 4.2 K to 100 mK. Preliminary measurements show no temperature dependence of the characteristic times of this random signal (~50 mS). This indicates that the switching event is a quantum phenomenon and is not thermally activated. We tentatively attribute this phenomenon to switching between two closely spaced tunneling channels.

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Photon Assisted Tunneling in Single and Coupled Quantum Dot Systems

Toshimasa Fujisawa and Seigo Tarucha
NTT Basic Research Laboratories
3-1, Morinosato-Wakamiya, Atsugi-shi, Kanagawa, 243-01, JAPAN

Resonant tunneling properties of discrete zero-dimensional (0D) levels have been intensively studied in semiconductor quantum dot systems. The optical properties of such systems are also interesting since they shed further light on the electronic structure. A photon-assisted tunneling (PAT) current can be detected with a high degree of sensitivity in a quantum dot with the aid of the Coulomb blockade effect.[1,2] PAT attracts interest as it permits investigation of time-dependent tunneling phenomena related to 0D levels and this may lead to the development of novel highly-sensitive microwave detectors.[2,3] In this talk, we describe PAT in single and coupled quantum dot systems which have a relatively large 0D level separation. We report the first observation of resonant 0D-0D PAT in a weekly-coupled double-dot system.

We use Ga focused ion beam implanted in-plane gates and Schottky gates to define single and double-dot systems in a two-dimensional electron gas.[4] Negative differential resistance is clearly observed as a result of resonant tunneling through 0D levels. Pronounced current peaks in the double-dot system are attributed to 0D-0D resonances, in which the current flows only when a 0D level in the dot I coincides with a 0D level in the neighboring dot II and inelastic tunneling between the dots is well suppressed. The microwave electric field is introduced to one of the Schottky gates via a co-planar waveguade and a coupling capacitance. The microwave (photon) energy, $h\nu$, of 210 μeV (ν = 50 GHz) is larger than the resonance width of each 0D quantum level and the thermal energy, but smaller than the 0D level spacings and the charging energies in each dot.

In a single quantum dot system, PAT takes place between a 2D reservoir and a 0D quantum level when the photon energy is larger than the energy difference between the Fermi energy of the reservoir and a 0D level. A microwave electric field applied across the tunneling barrier leads to the formation of a sideband structure which results in PAT current peaks in addition to the Coulomb oscillation peaks. In the case of a coupled quantum dot system, resonant 0D-0D PAT is observed only when the 0D levels in the neighboring dots are exactly separated by the photon energy. PAT from an occupied state in dot I to an empty state in dot II enables an electron flow from the source to the drain. On the other hand, PAT from an occupied state in dot II to an empty state in dot I leads to an electron flow in the opposite direction. We find that 0D-0D PAT resonant peaks are sharper than those associated with the main 0D-0D resonant tunneling process in accordance with time-dependent resonant tunneling theory.[3] Furthermore, a multiple photon absorption process is also observed in a strong microwave field. The photon *stimulated emission* associated with PAT from a higher lying occupied level to a lower lying empty level is obtained at a sufficient drain voltage such that population inversion takes place.

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MAGNETOTUNNELLING SPECTROSCOPY IN A SINGLE AlAs BARRIER INCORPORATING InAs QUANTUM DOTS

A. Thornton, I.E. Itskevich, T. Ihn, M. Henini, P. Moriarty, A. Nogaret, P.H. Beton, L. Eaves and P.C. Main

Department of Physics, University of Nottingham, Nottingham NG7 2RD, UK

We have investigated electron tunnelling through a single barrier GaAs/AlAs/GaAs heterostructure in which Stranski-Krastanov-grown InAs quantum dots are incorporated in the centre of the barrier. At 4.2K the I-V curves exhibit pronounced peaks which are absent in a control sample grown without InAs in the AlAs barrier. For magnetic field, B, parallel to the current, each peak splits into a set of sharp components at fields as low as 0.4T (see Fig. 1). They correspond to the Landau level quantisation of the electron states in the emitter accumulation layer. This proves that each peak arises from tunnelling into a *single* discrete 0D-state in the tunnel barrier. Measurements at 300mK reveal a rich fine structure of the peaks indicating that electron-electron interactions are important. Applying B perpendicular to the current modifies the fine structure significantly and very sharp isolated resonances occur in the I-V-curves (see Fig. 2).

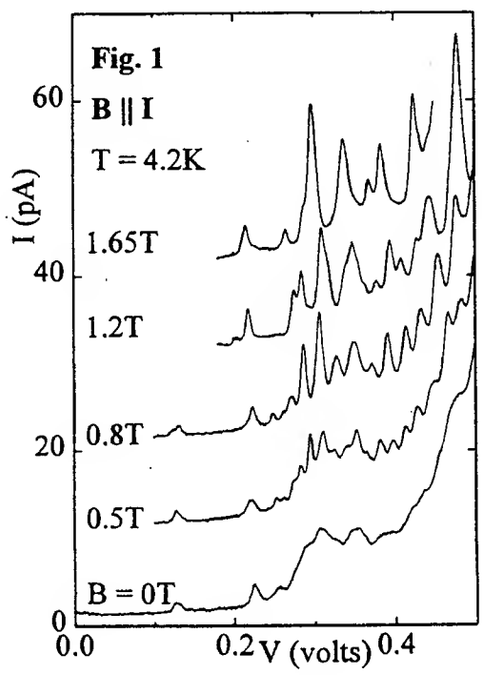

Fig. 1: I-V curves at 4.2K in parallel magnetic fields. Curves are offset in current for clarity.

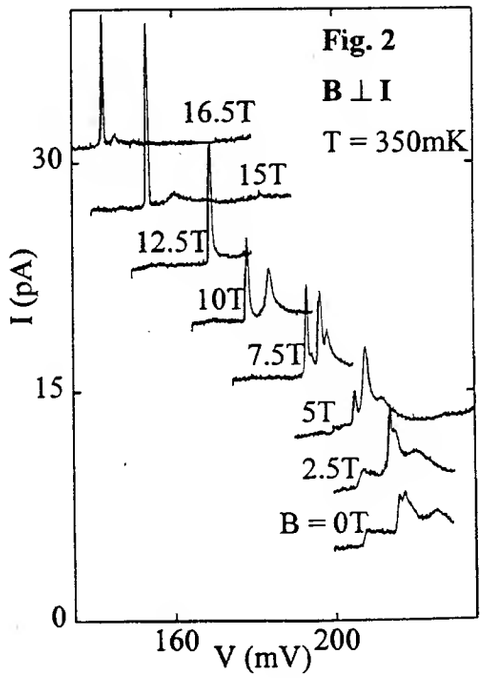

Fig. 2: Fine structure of a peak at 350mK and different perpendicular fields. Curves are offset in current for clarity.

Memory Effect Double-Barrier Resonant Tunnel Diode with InAs Dots Observed at Room Temperature

Kanji Yoh, Takaya Nakano
Research Center for Interface Quantum Electronics, Hokkaido University
N13, W 8, Kita-ku, Sapporo 060, Japan

We have observed a memory effect in current voltage characteristics at up to 300K in a GaAs/AlGaAs double-barrier resonant tunneling diodes(DBRTD) with self-assembled InAs dots formed on the cathode side of the barrier. The memory effect is likely to be caused by the charging of hot electrons into InAs dots and decharging of the trapped electrons through tunnling via resonance states in the adjacent double quantum well.

So far, most apllications of the quantum dots were restricted to lateral transport devices such as HEMTs [1] and MOSFETs[2][3] except semiconductor LASER diodes[4] . Here, we report a new type of DBRTD with bistable characteristics caused by charging effect of InAs dots operated at room temperature.

The MBE grown heterostructure of the DBRTD consist of 6,000Å n^+-GaAs, 40Å of GaAs, 40 Å of AlGaAs barrier, 40Å of GaAs well, 40Å of AlGaAs barrier, 20Å of GaAs, effectively 2.5ML of InAs, 20Å of GaAs and 1,445Å of n^+-GaAs/n^+-InGaAs/n^+-InAs graded layer. The lateral size of the measured devices is 5μm. The average areal density of the dots was $4x10^{10}cm^{-2}$ resulting in 10,000 dots per device. The average size of the self-assembled InAs dots were 80Å in height and 500Å in diameter. In the present structure, the size distribution of the dots were made so random that the electron distribution becomes continuous from the bottom of the bulk conduction band minima, so that the corrent voltage characteristics in forward bias show blurred negative resistance at the resonatce condition of the control sample without InAs dots.

When the scanned voltage exceeds resonant tunneling condition in both polarities, typical hysterisis curve is obtained. The switching between off-state (charged) and on-state (discharged) was clearly demonstrated and their two-terminal resistance at zero bias were 3.4kΩ and 150Ω, respectively, at room temperature. When the device is negatively biased exceeding the resonance condition, InAs dots were found to be filled with electrons. On the other hand, the discharging of the InAs dots are initiated when the positive bias exceeds resonance condition (between 0D and 2D states). Besides, distinct current oscillations were observed in the voltage region of charging and discharging of InAs dots. However, the physical origin of these oscillations are presently under investigation. The present result opens up a possible novel application of Coulomb blockade phenomena to vertical transport devices such as RTD, LED, APD and LASERs.

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papers per title

Raman Scattering from a Magnetically Modulated 2DEG Subject to a Normal Magnetic Field

V. Fessatidis[a], H. L. Cui[b], and P. Vasilopoulos[c]

[a] *Department of Physics, Fordham University, New York 10458 U.S.A.*

[b] *Department of Physics and Engineering Physics, Stevens Institute of Technology Hoboken, New Jersey 07030 U.S.A.*

[c] *Department of Physics, Concordia University Montreal, Quebec, Canada H3G 1M8*

E-Mail: hcui@phdec1.stevens-tech.edu Fax: (201)216-5638

An analysis of electronic Raman light scattering from a two-dimensional electron gas (2DEG) subject to a *weak periodic* magnetic modulation of strength B_0 and to a perpendicular uniform magnetic field B of arbitrary strnegth is presented. Raman spectra are calculated for: i) electron inter-Landau-level transitions, which result in a Raman shift $\sim 2\omega_c$, bearing corrections due to the finite width of the Landau levels resulting from the modulation; ii) inter-Landau-level collective electron excitations at both the hybridized magnetoplasmon frequency and at a *new* low-frequency, an intra-Landau-level plasmon mode induced by the modulation. The dependence of the Raman cross sections on the strength of B and B_0 is assessed. Both 1D or 2D spatial modulations of the magnetic field (achievable, *e.g.*, by patterned deposition[1] of magnetic materials on top of the AlGaAs layer of the quantum well containing the 2DEG, are considered and their effects on the Raman spectrum are investigated and compared with those of the electric modulation. The effects of a weak B_0 on the Raman spectrum are in one to one correspondence with those of the electric modulation[2] but the magnetic modulation leads to much stronger Raman signals. The combined effect of 1D electric and magnetic modulations is also considered. It is shown that electronic Raman scattering provides an independent, spectroscopic probe of the physics of these modulated structures. In conjunction with this, possible experimental forms of the many-faceted Raman spectra are indicated and analyzed.

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Indirect Intersubband Transitions in Short Period GaAs/AlAs Superlattices

A. Fenigstein, E. Finkman, G. Bahir, and S. E. Schacham*

Dept. of Electrical Engineering and Solid State Institute, Technion Israel Institute of Technology Technion City, Haifa 32000, ISRAEL

**Dept. of Electrical and Electronic Engineering, College of Judea and Samaria, Ariel, ISRAEL*

Indirect intersubband transitions were observed for the first time in GaAs/AlAs type II short period superlattices (SPS) using current induced absorption [1]. Two SPS were studied, both constructed of 50 periods, each consists of 6 monolayers of GaAs "wells" and 8 monolayers of AlAs "barriers". The SPS were "sandwiched" between a 1 μm n-type GaAs bottom contact layer, and 0.5 μm top p-type contact, to enable modulation of carrier concentration in the SPS by injection of current. The SPS itself was undoped in the first sample, while the AlAs layers in the second sample were n doped by Si to 10^{18} cm^{-3}. Significant absorption of radiation polarized in the "forbidden" parallel polarization was measured, in addition to the "allowed" perpendicular component. The absorption is shown to be strongly temperature dependent (see Fig. 1). Thus, direct X-X or Γ-Γ transitions are excluded, and the observed transition is attributed to Γ–X mixing. Simulations of such absorption using a two band model show good agreement to experimental data, with derived fitting parameters of the valence band offset $\Delta E_v = 0.49$ eV, and Γ–X mixing coefficient $\gamma = 8$ meV.

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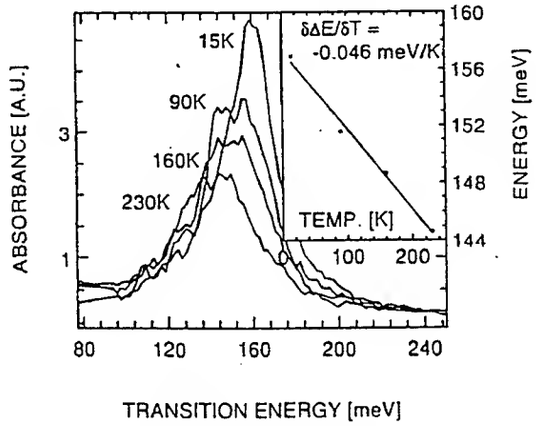

Fig. 1. Temperature dependence of the infrared X-Γ absorption peak.

Analytical Model of High-Frequency Photoconductivity in Quantum Well Infrared Photodetectors

M. Ershov and V. Ryzhii

Computer Solid State Physics Lab., University of Aizu, Aizu-Wakamatsu, 965-80 Japan

Phone: (81-242) 37-2566, Fax: (81-242) 37-2596, Email: ershov@u-aizu.ac.jp

Recently there has been a strong interest in high-speed and high-frequency applications of Quantum Well Infrared Photodetectors (QWIPs) [1]. High-frequency operation of QWIPs involves a number of physical effects, including carrier transport in the QW structure, capture to the QWs, emission from the QWs into the continuum states, and recharging of the QWs. In a recent paper [2] we showed using computer modeling that QWIP's response to a step-like infrared excitation consists of a fast and a slow components. High-frequency capabilities of QWIPs are due to the fast transient, which has a characteristic time of a few picoseconds. The existing theories of QWIP can not explain what physical effects are responsible for the QWIP transient response, and how do QWIP structural parameters and operating conditions influence its high-speed and high-frequency performance. In the present work we present an analytical model of QWIP photoconductivity at high frequencies which gives an answer to these questions.

The analytical model is derived from a full self-consistent model of QWIP [2]. We made the following simplifying assumptions: potential distribution in QW structure is independent of time, electron drift velocity is constant, and generation rate for the continuum states electrons due to photoionization of electrons from the QWs is uniform and constant over the QW structure. The first assumption means there is no extra injection of carriers from the injecting contact related to photocurrent. This takes place at infrared radiation frequencies higher than the inverse characteristic time of QW recharging τ. Under these assumptions the QWIP's model reduces to current continuity equation which is a first-order differential equation with constant coefficients. The model operates with three parameters – electron transit time through the QW structure τ_{tr}, capture time to the QWs (life-time) τ_c, and drift velocity v. Explicit analytical expressions for transient photoexcited carrier concentration and photocurrent both in the frequency domain and the time domain are obtained. Due to non-quasi-static effects the photoexcited electron concentration is not uniform over the QW structure, increasing from 0 at the injecting contact as $(1 - \exp(-x/L_c))$, where $L_c = \tau_c \cdot v$ is the capture length. Photocurrent is due to the electrons photoexcited from the QWs and extracted from the QW structure by applied field, i. e. primary photocurrent is not multiplied by extra electron injection. Frequency-dependent responsivity is given by:

$$R(\omega) = \frac{R_0(\omega)}{1 + i\omega\tau_c}, \qquad R_0(\omega) \sim v\tau_c \left\{1 - \frac{\tau_c}{\tau_{tr}} \frac{1}{1 + i\omega\tau_c} \left[1 - \exp\left(-(1 + i\omega\tau_c)\frac{\tau_{tr}}{\tau_c}\right)\right]\right\}.$$

Non-quasi-static responsivity R_0 deviates significantly from static responsivity in the case $\tau_c/\tau_{tr} \gg 1$, i. e. in the case of high photocurrent gain. The photocurrent gain greater than unity is not exhibited at frequencies $\omega \gg 1/\tau$. At frequencies $\omega < 1/\tau$ responsivity decreases with the decrease of ratio τ_{tr}/τ_c, while it is independent of this ratio for $\omega > 1/\tau_{tr}, \tau_c$.

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Off–diagonal coupling of exciton states in novel superlattices and bulk III-V semiconductors in optoelectronic modulators, measured with modulation ellipsometry and compared with density matrix models

H. Mikkelsen, T. Dekorsy[1], S. Hunsche[1], O. Hunderi and H. Kurz[1]
Institute of Physics, Norwegian Institute of Science and Technology, N–7034 Trondheim, Norway. e-mail: mikkelse@phys.unit.no
[1] *Institute of Semiconductor Electronics 2, RWTH, D–52074 Aachen, Germany.*

The diagonal and off–diagonal coupling of the exciton states in novel short period superlattices used in optoelectronic modulator devices are measured using modulation ellipsometry. Complementary density matrix calculations of the dielectric function of these materials, and finally the reflection or transmission spectra of the devices, are used to increase the understanding of such materials. The model includes a modulating electric field and exciton transitions. In these structures, the off–diagonal Coulomb potentials couple the three–dimensional exciton eigenfunctions, making numerical calculations complex. We calculate the response of optically pumped superlattice modulators and compare to experimental optical spectra demonstrating the Coulomb enhanced Wannier Stark effect.

We also study a closely related phenomena, the Coulomb enhanced Franz Keldysh effect, in the active GaAs layer of an optoelectronic modulator. The exciton dissociates due to a transient electric field, modulating the dielectric function and transmitted light. The internal electric field redistributes within a few picoseconds after a low density pulsed optical excitation and is calculated from a drift–diffusion model. The optical transmission is calculated with a transfer matrix method, and compared to the experiments which have a time resolution of 100 fs. The effect of the Coulomb interaction and nonuniform electric field and GaAs velocity overshoot strongly influence the optical spectra and are included in our models.

First Observation of Electrically-resettable Persistent Photoconductivity

F.C. Wang,* W. Zhang,* C. H. Yang,* M. J. Yang,† and B.R. Bennett†

*Electrical Engineering Department, University of Maryland, College Park, MD 20742, U. S. A.

†Naval Research Laboratory, Washington, D. C. 20375, U. S. A.

The persistent photoconductivity in semiconductors has been thought to be related to DX-centers, which is characterized by a metastable-to-stable transition involving lattice relaxation. The transition is irreversible and thereby persistent at low temperatures when the activation energy is much greater than the thermal energy. While the DX-center is successful in explaining the positive persistent photoconductivity phenomena in, e.g., $Al_xGa_{1-x}As$, here we provide experimental evidence to show that the commonly observed negative persistent photoconductivity in the InAs/AlSb single quantum well system is owing to the ordinary deep-donor-like states in the AlSb barriers. Our sample is a single InAs quantum well, sandwiched by AlSb barriers. The substrate is doped and used as backgate. Multiple periods of a new AlSb/GaSb smoothing superlattice in the buffer layer are successfully used as the backgate dielectric. Two-dimensional electron density in the InAs quantum well decreases when the sample is illuminated. The decrease in electron concentration is persistent as long as the sample is kept at low temperature. We find, however, that *a momentary bias to the backgate can restore the electron concentration*. Numerical modeling using realistic parameters and physical assumptions provides insight into the mechanism, and we will discuss our picture that can quantitatively explain the observed features. Our observation on the electron concentration dependence on the backgating voltage indicates that the deep donors are located at 0.41 ± 0.05 eV above the AlSb valence band maximum, with a concentration in between 4×10^{16} cm^{-3} and 10^{17} cm^{-3}. The origin of the deep donors is probably from Sb-on-Al anticite defects.

SUPPRESSION OF INTERSUBBAND SCATTERING IN A SUBCHANNEL

B.K.Ridley, M.Babiker and N.A. Zakhleniuk

Department of Physics, University of Essex, Colchester, UK

Incorporating a monolayer of a foreign material in a quantum well changes the optical-phonon spectrum. Choosing the monolayer to have optical-phonon frequencies significantly different from those of the quantum well material causes a vibrational node to appear at the monolayer. The electron wavefunction will also be modified. We analyse the effect of a centrally-placed polar monolayer on the polar-optical-phonon interaction with electrons using two continuum models for the optical modes, namely, the hybrid model and the dielectric continuum (DC) model. In the hybrid model we take the monolayer to be dielectrically neutral insofar as it supports no interface modes. Symmetrical hybrid modes are shown to be unaffected by the presence of the monolayer, and therefore there is no reduction of the intersubband rate. On the other hand, antisymmetrical modes are modified, and this leads to a reduction of the intersubband scattering rate. The DC model is applied with two different assumptions: (a) as in the hybrid model the monolayer is dielectrically neutral, and (b) the monolayer can be represented as a thin polar dielectric supporting interface modes. The results of both DC models are compared with the results of the hybrid model. The complementary forms of the DC and hybrid modes give rates for individual modes different to those of the hubrid model. The total DC rate is heavily dependent on the assumption made concerning the existence of monolayer interface modes. In the special case of a non-polar monolayer only the hybrid model is applicable. The conclusion is that a monolayer tends to reduce the intersubband rate but to leave the intersubband rate unaffected.

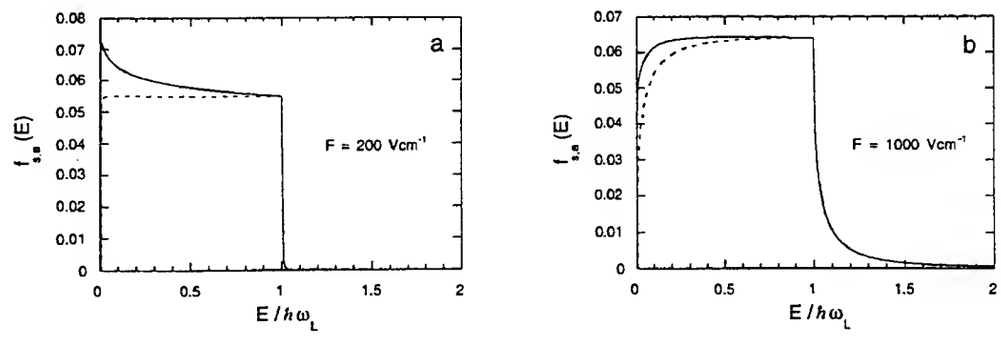
NEW DISTRIBUTION FUNCTIONS AND HOT-ELECTRON TRANSPORT IN QUANTUM WIRES

N. A. Zakhleniuk, C. R. Bennett, N. C. Constantinou, B. K. Ridley and M. Babiker

Department of Physics, University of Essex, Colchester C04 3SQ, UK

The kinetic theory of a non-equilibrium electron gas in a one dimensional circular quantum wire interacting with interface roughness and acoustic and polar optical phonons is developed. At high lattice temperatures (>40K) the electron-acoustic phonon interaction has a quasi-elastic character for the majority of the electrons at any strength of the electric field. As a result the total energy of the 1D electron gas gained from the electric field increases more rapidly than the energy loss due to the quasi-elastic interaction with acoustic phonons. In order to stabilize the electron system it is necessary to take into account the interaction with optical phonons.

Here we deal with relatively thin quantum wires (<100Å) in which the intersubband separation is much larger than the optical phonon energy. We have solved the Boltzmann kinetic equation analytically and obtained new distribution functions for a one dimensional electron gas. A detailed kinetic analysis of the limiting case of the electron gas interacting solely with optical phonons is undertaken and the distribution function is found when this system can be described in a self-consistent way. In the figures a and b the symmetric (solid) and antisymmetric (dotted) distribution functions are shown for different electric field F. Our analytical results are in good agreement with other studies of a similar system using Monte Carlo techniques. As an application of the developed theory we have calculated the electric field dependences of electron mobility and average energy for different parameters of the quantum wire. It is found that the electron mobility is a non-monotonous function of the applied electric field.



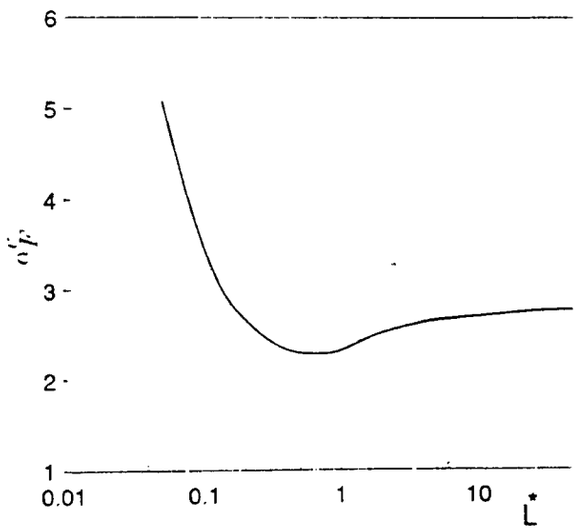
BIPOLARONIC EFFECTS IN QUASI ONE DIMENSIONAL QUANTUM WIRES

V. M. Fomin*,**, E. P. Pokatilov*, J. T. Devreese**, S. N. Balaban*, L. C. Fai*

*State University of Moldova, str. Mateevici, 60, 277009 Kishinev, Republic of Moldova

**Universiteit Antwerpen (U.I.A.), Universiteitsplein, 1, B-2610 Antwerpen, Belgium

The bipolaron binding energy $W = 2E_p - E_b$ (E_p is the polaron energy, E_b is the bipolaron one) is calculated as a function of the geometrical parameters characterizing quantum wires (QW's) and for different electron-phonon coupling constants α_F. It is known that for decreasing dimensionality of a structure (3D $\rightarrow$2D $\rightarrow$1D $\rightarrow$0D) polaron effects are enhanced, but the number of independent directions of charge transport is decreasing. From this point of view, quasi 1D QW's are interesting as structures with maximal polaron effect under the condition of existence of at least one charge transport direction. Therefore, these structures are promising for the observation of strong-coupled bipolarons and the possible effect of bipolaron superconductivity. Bipolaron states are considered in quasi 1D QW's of two types: cylindrical and planar ones, where electron confinement is imposed by a parabolic potential. The interaction between the electrons is described by 3D Coulomb potentials of corresponding symmetries, and Fröhlich 3D Hamiltonian is chosen to describe the electron-phonon interaction. Two approaches were used for calculations: interpolation variational theory (IVT) and Feynman-Jensen variational principle (FVP). Both methods were applied to each type of QW. Polaron energy $E_p(\alpha_F, R(L))$, bipolaron one $E_b(\alpha_F, R(L))$and subsequently bipolaron binding energy $W(\alpha_F, R(L))$ were calculated. Threshold values α_F^c at which polaron attraction compensates Coulomb repulsion exactly, are determined by the condition: $W(\alpha_F^c, R(L)) = 0$ at $\eta \equiv \varepsilon_\infty/\varepsilon_0 = 0$. Results of numerical calculations obtained for the planar QW within the IVT approach, are shown in the figure. It follows from the plot of the function $\alpha_F^c(L^*)$ (where $L^* = L/L_p$, $L_p = (\hbar/2m\omega_0)^{1/2}$, ω_0 is the longitudinal optical phonon frequency) that at intermediate $L^* = 0.6$, α_F^c reaches its minimal value $\alpha_F^c = 2.2$, which is smaller than the value at large $L^* \geq 10$ (the planar case), when $\alpha_F^c = 2.8$. For further decreasing L^*, α_F^c increases rapidly, so that $\alpha_F \gg 1$ must be imposed again for the realization of bipolaron states. The results obtained are confirmed qualitatively also within the FVP approach, especially increase of α_F^c with decreasing $R(L)$, in both cases (cylindrical and planar QW). These conclusions seem to contradict those obtained in Ref. [1] for a 1D quantum wire. The reason is the following: in Ref. [1] the fully 1D model is used, i. e. 1D electron confinement, 1D phonons, and 1D Coulomb interaction. The last reason is especially significant, since 1D Coulomb potential has δ-like form, so that the repulsion of electrons takes place at direct contact only.



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LEAD DEPHASING IN NONEQUILIBRIUM TRANSPORT THROUGH QUANTUM DOTS

Ben Yu-Kuang Hu[1] and **X. C. Xie**[2]

[1] *Mikroelektronik Centret, Danmarks Tekniske Univ., DK-2800 Lyngby, Denmark.*

[2] *Department of Physics, Oklahoma State University, Stillwater OK 74078, USA.*

There has been considerable activity in the theoretical study of nonequilibrium transport through phase-coherent quantum dots [1], leading to predictions of many quantum phenomena such as photonic sidebands and Kondo peaks in the conductivity. In these studies, the electrons in the leads are always assumed to be *non-interacting*. This is equivalent to assuming that phase coherence, which is at the root of many of the predicted quantum phenomena, is always maintained when carriers are in the lead. However, for highly nonequilibrium situations, many electrons are injected into states far away from the Fermi surface, where dephasing from electron–electron (e-e) interactions is a dominant process. We study the effect of these dephasing e-e interactions in the leads by using the Keldysh formulation of quantum transport. We find that inclusion of these interactions leads to two classes of Feynman diagrams. The first class, in which lead e-e interaction lines are not intertwined with the hopping processes in and out of the dot, result in a renormalization of the density of states in the lead, and does not change the transport properties significantly. However, diagrams of the second class, where lead e-e interactions and hopping in and out of the dot are intertwined, result in significant dephasing which dramatically reduce the effects of quantum phenomena that are rooted in phase-coherence. We outline the experimental parameters over which we expect lead-scattering-induced dephasing to become important in the systems theoretically studied previously.

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PERSISTENT CURRENT WITH FRACTIONAL PERIOD IN A MULTICHANNEL WIGNER CRYSTAL RING

A.A. Krokhin[1] and I.V. Krive[2]

[1] Instituto de Física, Universidad Autónoma de Puebla,
Apdo. Postal J-48, Puebla, 72570, Mexico.

[2] B.I. Verkin Institute for Low Temperature Physics and Engineering
47 Lenin Avenue, 310164, Kharkov, Ukraine.

In the ballistic semiconductor quantum ring the effects of Coulomb interaction play important role because of low concentration of carriers. In particularly, the effects of electron-electron correlations change drastically the persistent current (PC) induced in a ring in comparison with the one for noninteracting electrons [1]. Due to this difference, the persistent current can be used for studing rather subtle non-Fermi-liquid effects in quasi 1D electron systems. So far the theoretical calculations of the PC for strongly correlated electrons were performed for strictly 1D case. Here we consider, for the first time, the PC in a multichannel Wigner crystal ring and demonstrate that not only the amplitude of Aharonov-Bohm (AB) oscillations depends on electron-electron correlations [1], but the period is also different from the fundamental one Φ_0.

We use the model of multicomponent Luttinger-liquid proposed in Ref. [2]. We proof that in the impurity-free ring the Wigner crystallization does not change the PC current in accordance with general theorem [3]. However a local electrostatic potential produced by a splitting gate impedes a free sliding of a crystal along the ring and leads to a strong suppresion of PC amplitude. We calculate the PC at $T = 0$ in two regimes of weak and strong pinning.

In both cases the amplitude of PC decays rapidly with the energy of the pinning barrier (gate voltage). In the strong pinning limit when the tunneling occurs according to the two-stage mechanism proposed by Larkin and Lee [4] we obtain the multielectron tunneling which is due to the interchannel Coulomb coupling. This leads to the AB oscillations with fractional period which depends on the fillings of the channels.

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TIME-OF-FLIGHT TRANSIENT PHOTOCURRENT IN $Ga_{0.5}In_{0.5}P$ ORDERED SUPERLATTICES

T. KITA, K. YAMASHITA, T. HAGIHARA, H. NAKAYAMA, and T. NISHINO
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kobe University, 1-1 Rokkodai, Nada, Kobe 657, JAPAN

Long-range ordering in GaInP produce monolayer superlattice of $Ga_{0.5+\eta/2}In_{0.5-\eta/2}P/Ga_{0.5-\eta/2}In_{0.5+\eta/2}P$ along the $[1\bar{1}1]$ and/or $[\bar{1}11]$ directions, where η is order parameter. The degree of ordering depends on growth conditions such as growth temperature, source-gas-flow ratio, and substrate orientations. Domains with different order parameter are statistically distributed in an ordered epitaxial film. Because of the band-gap reduction by a band folding in ordered superlattice, the statistical distribution of order parameter causes a potential fluctuation. This fluctuation plays an important role in optical and electrical properties in the ordered epitaxial films. In this study, we focus our attention on transient phenomena of photo-excited electrons in ordered GaInP with different order parameter.

Non-dope GaInP were grown on n^+-GaAs(001) by organometallic vapor-phase epitaxy. The degree of ordering was controlled by growth temperature. In this experiment, mean order parameter of the epitaxial films was estimated from an optical absorption edge energy. Time-of-fight measurements have been performed to semitransparent-Au/GaInP Schottky-barrier diode by detecting transient photocurrent excited by a 300 ps flash of light from a N_2 laser of wavelength 337 nm. Since the penetration of the excitation laser is about 10 nm, the transient current reflects dynamics of electrons drifted through the junction. The transient current was measured from 20 K to 300 K with 20 K step. Figures 1(a) and 1(b) show *Jxt* spectra measured at various temperature for ordered GaInP with η=0.58 and 0.14, respectively. Here, *J* and *t* are photocurrent and its delay time. The *Jxt* spectra of the ordered GaInP with η=0.58 [Fig. 1(a)] show a dramatic change with decreased sample temperature, in contrast to that of η=0.14 [Fig. 1(b)] which shows monotonous decrease at any temperature, though a change of the slope was observed between 200 K and 220 K. According to analysis of carrier trapping events for drifted electrons, it is found that the observed temperature dependence of the *Jxt* spectra is a feature of exponentially distributed trap states. The different trend for the different degree of ordering indicates that the localized state density depends on degree of ordering. We will discuss about temperature dependence of effective drift mobility as well as spatial band lineup of ordered alloys.

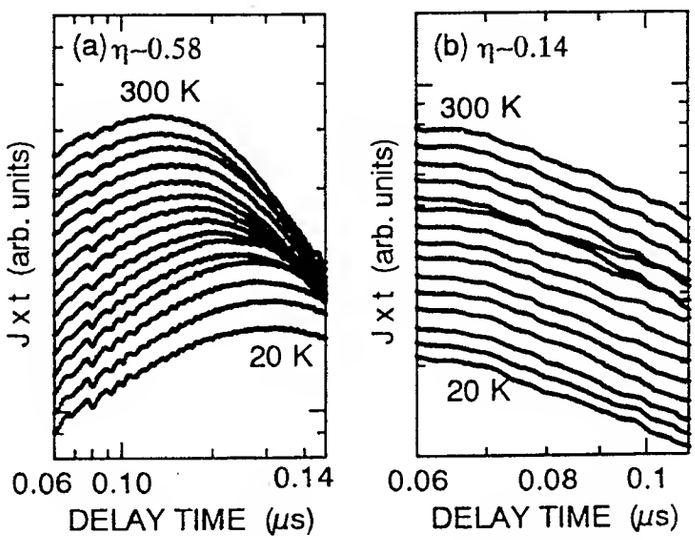

FIG. 1 Jxt spectra of ordered superlattice with (a)η~0.58 and (b) η~0.14.

THE ROLE OF INTERFACE BROADENING ON THE PHONON MODES OF Si/Ge SUPERLATTICES

A. M. R. Teixeira, M. A. Araújo Silva, R. N. Costa Filho, G. A. Farias, and V. N. Freire

Departamento de Física, Universidade Federal do Ceará, Caixa Postal 6030

Campus do Pici, 60455-760 Fortaleza, Ceará, Brazil

Recently, both theory and experiments have shown that the existence of intermixed SiGe alloy layers can modify the vibrational properties of Si/Ge superlattices, and even be responsible for an interface mode [1]. The purpose of this work is to present results on how the interface broadening changes the phonon modes of Si/Ge superlattices. The nonabrupt superlattices $Si_n(SiGe)_mGe_n(SiGe)_p$, with 2n+m+p=constant, are described by a linear chain model, and also by using a continuous model where the mass is assumed to be position dependent. It is obtained that the splitting of the folded LA modes and the frequencies of confined LO modes in the Γ, X directions are sensitive to the interface sharpness. The splitting of the second and third folded LA modes in the Γ direction almost disappear in the case of $Si_9(SiGe)_3Ge_9(SiGe)_3$ and $Si_{10}(SiGe)_2Ge_{10}(SiGe)_2$, respectively. It is shown that the existence of interfacial asymmetry (m≠p) can change also the phonon frequencies.

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A MICROSCOPIC THEORY OF SKYRMION EXCITATIONS AT FRACTIONAL FILLING FACTORS

Kang-Hun Ahn, J. H. Oh, and K. J. Chang

Department of Physics, Korea Advanced Institute of Science and Technology, Taejon 305-338, Korea

In a two-dimensional electron gas at Landau level filling factor $\nu = 1$, the ground state is ferromagetic. However, in the limit of weak Zeeman coupling, it is now accepted that the lowest energy charged excitations of this system are spin textures known as skyrmions, which are evidenced by recent NMR and magnetoabsorption spectroscopy measurements. Previous theoretical studies of skyrmions have been successful in predicting the net spin of skyrmion, however, they have been restricted to the quantum Hall systems near $\nu = 1$. Here we develope a microscopic approach to the skyrmion excitations of the ferromagnetic incompressible ground state, which occur in the quantum Hall system at various filling factors $\nu \leq 1$. At $\nu = 1$, our calculational results are found to be consistent with the results of Fertig *et. al.*[1] At an odd-denominator filling factor, $\nu = 1/3$, we find that the excitation gap which is the energy required to create a skyrmion-antiskyrmion pair is lower than the excitation gap of a quasihole-quasielectron pair, in good agreement with the macroscopic theoretical results of Sondhi *et. al.*[2] We investigate the relation of the physical charge to the topological charge at fractional filling factors from a microscopic point of view. The net spins of skyrmion excitations, which are determined by a competition between the Zeeman coupling and the Coulomb interaction, are calculated as a function of magnetic field.

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e-mail : kchang@convex.kaist.ac.kr

Excited states of donors bound to X valleys in GaAs-AlAs type II structures

Gerald Weber* **and Gleise N. Carneiro+**
**Grupo de Física dos Sólidos e Eletrônica Quântica, Instituto de Pesquisa, Universidade São Francisco, 13251-900 Itatiba SP, Brazil*
+Faculdade de Engenharia de Joinville, Universidade do Estado de Santa Catarina, 89223-100 Joinville SC, Brazil

In the last years there has been an intense theoretical and experimental effort in the study of shallow impurities in type I quantum well structures. Although some authors considered the influence of the Γ-X mixing in type I quantum wells there has been no study of donors in type II structures where the lowest lying conduction band energy state is in the X valley. In such type II quantum wells the interband transition of lowest energy is indirect in real space and the donors are bound to the X valleys of AlAs. These valleys have a pronounced effective mass anisotropy and the $X_{x,y}$ and X_z valleys are no longer degenerate.

In this work we extend a variational procedure used for the calculation of the ground state bding energy of a donor in a type-II quantum well [1] to calculate its excited states. We employ three variational parameters in our $1s$-like trial wave function in order to take into account the effective mass anisotropy and the quantum confinement. We assume that the X valleys can be considered independently, a situation characteristic to substitutional Si donors in bulk AlAs and which allows to use a similar effective mass hamiltonian as for the type I case. For a comparative study, we use two sets of effective masses obtained from different measurements [2, 3]. We show that the binding energies have a pronounced dependence with the effective mass, AlAs layer thickness and impurity position.

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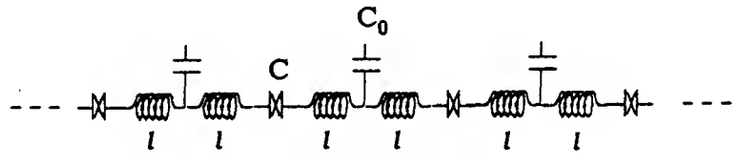
Single Electron Tunneling and Collective Oscillations in Quantum Dot Matter

M. Stopa
RIKEN, The Institute of Physical and Chemical Research

We study dynamical properties of arrays of quantum dots by introducing internal island inductances ℓ into the standard circuit model for coupled tunnel junctions. In the absence of tunneling and disorder we derive the dispersion relation for collective oscillations in terms of the internal inductances, the junction capacitances C and the island capacitances to ground, C_0. The frequency, which goes as $\omega_k = \frac{1}{\sqrt{2\ell C}}\sqrt{1+\frac{k^2 C}{C_0}}$, is shown to be independent of the number of charges trapped on the islands. For typical semiconductor quantum dot arrays, comparison with experiment shows that $\omega_0 = \frac{1}{\sqrt{2\ell C}}$ is in the FIR.



quantum dot matter 1d

Single electron tunneling (SET) is introduced first by expanding the charge change of one event in terms of the normal modes. The evolution of the expanding pulse is determined within the steepest descent approximation. It is shown that, for an array of N junctions biased (uniformly) in the vicinity of tunneling threshhold, the tunneling across a single junction can produce a cascade effect resulting in a nearly coincidental tunneling across all junctions. This process, essentially one of charge density wave tunneling, is substantially more probable than completely independent tunneling would predict, going as $\sim 1 - exp(-\sum_i^N \Gamma_i t)$, where Γ_i is the tunneling probability across the i^{th} junction for some given bias condition. In the case of independent tunneling, a probability of $1 - \sum_i^N exp(\Gamma_i t)$ would arise.

Recently the experiments of Kotthaus *et al.* [1] on the response of an array of quantum dots to FIR light as the SET regime is broached, have generated considerable interest. Employing a probability density function to describe tunneling in the harmonic regime, we show that the onset of tunneling precipitates a fracturing of the principal resonance into a set of lower frequencies $\omega_n = \frac{1}{n\sqrt{\ell C}}$, n an integer. These modes correspond to charge wave slipping by n sites. A similar fracturing of the resonance is observed experimentally, but only for non-zero magnetic field B. We argue that the Q-factor of the dot response is significantly enhanced with B by virtue of the internal (cyclotron) degree of freedom.

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A Cathodoluminescence Study of Strain Relaxation in GaAs/InGaAs MQW Diodes

P.R.Griffin, J. Barnes, K.W.J. Barnham, M.Mazzer, C.Zanotti-Fregonara, G. Haarpaintner

Imperial College of Science, Technology and Medicine, London SW7 2BZ, UK.

Lattice mismatch between semiconductor materials creates strain which can be relaxed by the formation of misfit dislocations (MDs). These dislocations,often being electrically active, influence the diode leakage current. The amount of strain that can be allowed in a structure without degradation of the diode characteristics is very important for device design. A series of devices have been studied with a strained-layer MQW of $In_xGa_{1-x}As$ (x = 0.155 to 0.23) quantum wells with GaAs barriers sandwiched between two GaAs regions, the upper one being p doped and the lower n doped. The structures are grown both by Metal-Organic Vapour Phase Epitaxy (MOVPE) and Molecular Beam Epitaxy (MBE) and comparison will be made. Groups of MDs are seen as dark lines when imaging the wafer with the cathodoluminescence (CL) mode of a scanning electron microscope (SEM). An image-processing program has been developed to count the lines and two different distributions and densities of dark lines are observed depending on whether the electron beam accelerating voltage (E_b) is above 25keV or below 20keV. The wafer is processed into photo-diode devices and the forward bias leakage current is measured up to a bias of 1.5V. For the first time a strong correlation is found between the magnitude of the diode current and the dark line density. Moreover, the dark line density and the forward leakage current increase with strain in two stages, the first when the MQW relaxes on formation of MDs at the lower interface and then on further relaxation by the production of MDs at the upper interface.

Enhanced electron resonant tunneling and Γ-X interlayer intervalley transfer in a triple-barrier heterostructure

Gyungock Kim, Dongwan Roh and Seung Won Paek

Research Department, Electronics and Telecommunications Research Institute

Yusung P. O. Box 106, Taejon, Korea 305-600.

The AlAs/GaAs triple-barrier heterostructure (TBS) provides usful tool in investigating the physics of electron tunneling phenomenon and Γ-X interlayer electron transfer. In this paper, we report experimental and theoretical study of electron tunneling and electronic structures of TBS. Incorporation of the second quantum-well structure to the asymmetric double-barrier system improves peak to valley current ratios considerably. We have observed the enhanced resonant tunneling effect in the current-voltage characteristics of the AlAs/GaAs (001) TBS, which comprises of thin outer barriers (~15 Å) and a thicker middle barrier, grown by molecular beam epitaxy. The resonant tunneling current peak through the ground quantum-well state, which was not detected in the double-barrier case, was detected in the 20x20 μm TBS with the peak to valley current ratio of ~2 at room temperature, due to the alignment of quasi-bound ground states of both quantum-wells. The thicker middle barrier is used in order to study the effect of X valley barrier states on electron transfer. The broad concave shape feature in I-V characteristic, which is due to electron transfer through X valley states of the middle barrier, was observed between two resonant tunneling current peaks through quantum-well confined states at low temperature. The effect of external field and the Γ-X interlayer intervalley transfer in the AlAs/GaAs (001) TBS were analyzed using the scattering theoretic Green's function technique incorporated with the multi-orbital tight-binding model.[1] The GaAs quantum-well state, which is above the AlAs X valley conduction band edge in energy, shows considerable mixing with AlAs barrier states. We also compare experimental results with the effective mass approximation calculation.

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EPITAXIAL GROWTH OF ZINC-BLENDE GaN ON SiC: A TOTAL ENERGY STUDY

L. M. R. Scolfaro [a], L. K. Teles [a], A. Josiek [b], R. Enderlein [a], J. R. Leite [a], and D. Schikora [c]

[a] *Instituto de Física, Universidade de São Paulo, C.P. 66318, 05389-970 São Paulo, S. P., Brazil*

[b] *Université Bordeaux, Domaine Universitaire-3, 33600 Pessac, France*

[c] *Universität/ GH Padeborn, Warburger Str. 100, 33098 Padeborn, Germany*

Recently, epitaxial layers of cubic (β)-GaN have been successfully grown on several substrates such as GaAs (100), Si (100), and cubic SiC (100). Hitherto, it seems that β-SiC is the most suitable substrate, since the lattice mismatch with zinc-blende GaN is lower than 4%. In this work, we investigate for the first time, from a theoretical point of view, the epitaxial layer growth of β-GaN on β-SiC. We employ a self-consistent tight-binding total energy calculation method to study the deposition of a few layers of cubic GaN on SiC (100), taking into account surface reconstruction and interface mixing. We adopt 2 x 2 supercells in which the total number of atoms varies from 40 to 52. Cohesion energies, atomic displacements, dangling bond occupancies, and surface reconstructions are calculated for a variety of epilayer systems. These include monolayers of Ga or N, single and double bilayers of GaN, on C- and Si-terminated substrate surfaces, and 50% interface mixing of the first deposited layer with the first layer of the substrate. Depending on the system, surface atoms dimerize symmetric or assymmetrically, leading to 2 x 1, 2 x 2, or c-2 x 2 surface reconstructions. At the substrate interface with the first epitaxial layer, it is found that N binds stronger than Ga, both to Si and C.

TuPPT-19

THE WIGNER-SEITZ-SLATER CELLULAR METHOD AS APPLIED TO CALCULATE ELECTRONIC STATES AND RELATED PROPERTIES OF n-TYPE δ-DOPING GaN SUPERLATTICES

J. R. Leite, L. M. R. Scolfaro, J. L. A. Alves, S. C. P. Rodrigues, and R. Enderlein

Instituto de Física da Universidade de São Paulo, C. P. 66318, CEP 05389-970 São Paulo, S. P., Brazil

Interest in the group-III nitride semiconductors has increased in the last few years, due to their potential for the development of light-emitting devices in the blue and UV spectral regions. The success in producing both *n*- and *p*-type doping in GaN epitaxial thin films has led to the demonstration of high brightness blue LEDs. In this work we carry out, for the first time, self- consistent miniband structure calculations of n-type δ-doped zinc-blende GaN superlattices (SLs). The Wigner-Seitz-Slater (WSS) version of the cellular method with space filling one-dimensional cells and exact point match boundary conditions is used to solve the Schroedinger equation [1]. The calculations are performed within the frameworks of the effective mass theory and the local density functional approximation for the exchange-correlation effects. The conduction band effective mass of GaN is extracted from *ab initio* Full Potential Linear Augmented Plane Wave (LAPW) total energy calculations. Minibands, potential profiles, miniband occupancies, and Fermi level positions are studied as a function of the spacing d between the δ-layers and the doping concentration N_D [2].

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ELECTRONIC STRUCTURE AND FAR-INFRARED ABSORPTION IN VERTICALLY COUPLED QUANTUM DOTS

J. H. Oh*, K. J. Chang*, G. Ihm†, S. J. Lee‡

* Department of Physics, Korea Advanced Institute of Science and Technology Taejon 305-338, Korea

† Department of Physics, Chungnam National University, Taejon 305-764, Korea

‡ Department of Physics, Korea Military Academy, Seoul 139-799, Korea

We calculate the electronic structure of quantum dots coupled along the growth direction[1] with one or two electrons in magnetic fields. We examine the spin transitions[2] of the ground states, the electronic charge distributions, and the optical transitions between the energy levels, which are associated with far-infrared radiation. Because of the dot-dot and electron-electron interactions, the coupled quantum dots exhibit rich electronic structures.[3] To see the effect of the Coulomb interaction on the energy levels, we calculate the oscillator strengths and find a blue shift in the transition energy for a vertically polarized light as the magnetic field increases, while independently of the magnetic field this shift can not be seen in the absence of the Coulomb interaction. In asymmetrically coupled quantum dots, electrons which are initially localized in a wider well at zero magnetic field tunnel into a narrower well as the magnetic field increases.

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Theory of excitons in quantum dots

M Boero, J M Rorison*, G Duggan*, J C Inkson
Department of Physics, University of Exeter, Exeter, EX4 4QL

*Sharp Laboratories of Europe LTD ,Edmund Halley Road,
Oxford Science Park, Oxford OX4 4GA

Quantum dot systems are confined semiconductor structures which exhibit a fully discrete spectrum due to the size confinement in all directions. The position of the energy levels inside such structures can be changed by adjusting their geometrical dimensions. Such structures are particularly interesting for optical applications for two reasons: firstly both the electrons and holes are confined in the same small physical region therefore the strength of recombination processes is increased, secondly by changing the position of the energy levels one can in principle tune quantum dot lasers over a wide range of wavelengths. The presence of size confinement gives rise to two competing effects: on one hand it causes an upward shift of the energy levels and on the other it enhances the Coulomb attraction between electrons and holes. These effects tend to shift the position of the exciton energies in opposite directions so that a careful modelling of such structures is required in order to understand which is the dominant effect and how the excitons behave as a function of confinement. While there have been several studies on ideal systems we attempt to model a system more closely aligned to experiment. We take as our model a cylindrical disk of quantum well(QW) material(GaAs) sandwiched between AlGaAs barriers. In this work we study excitons in quantum dots by using two models for the size confinement, namely a parabolic potential and a hard-wall one. Within the parabolic potential we propose a model which is exactly solvable. In general we find that the excitonic binding energy can be calculated with good accuracy by using perturbation theory and depends on the shape of the confining potential. We also account for the finite spread of the electron and hole wave functions along the growth direction, which proves to be important. We also attempt to model the effective mass change for the holes which varies from QW-like values for large disks to bulk-like values for small disks. Comparison with the experimental results is in general good.

GIANT POLARIZATION CONVERSION BY TWO-DIMENSIONAL ARRAY OF QUANTUN DOTS OR POLAR NANOCRYSTALS IN AN EXTERNAL FIELD

Yuriy A. Kosevich, Surface and Vacuum Research Center, 117334 Moscow, Russia

We study the resonant interaction and the related polarization conversion of the far-infrared radiation with two-dimensional (2D) system of quantum dots in perpendicular magnetic field, or with 2D system of polar ionic nanocrystals in perpendicular electric field. As an example of the latter system we consider 2D system of semiconductor (such as *PbS*) nanocrystals embedded in dielectric (polyvinyl) thin film, in which the coupled optical-phonon vibrational modes have been recently observed [1]. The wavelength of the incident light greatly exceeds the average size of a quantum dot or a nanocrystal as well as the thickness of supporting thin film, and therefore the radiation in both considered cases interacts with effective *continuous* polarizable 2D systems. We predict that a giant, almost *total* polarization conversion of the reflected infrared radiation, between transverse electric and transverse magnetic light or vice versa, can occur in 2D system at simultaneous resonance with *two* eigenmodes, a *local* and a *collective* one, namely with the cyclotron and 2D magnetoplasmon-polariton modes in 2D array of quantum dots in perpendicular magnetic field or with the coupled optical-phonon and 2D optical-phonon-polariton modes in 2D system of polar nanocrystals in perpendicular electric field. These double-resonant optical phenomena are guided by the spectral and polarization properties of the local and collective eigenmodes in the effective 2D (planar) nanostructure. The considered phenomena predict new possibilities for the use of planar nanostructures, including non-magnetic ones, in efficient tunable switching devices.

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SPATIO-TEMPORAL DYNAMICS OF LIGHT EMISSION FROM GUNN DOMAINS

M. Hostut, N. Balkan
University of Essex, Department of Physics, Colchester, UK

ABSTRACT

We report the experimental studies on light emission from n-GaAs epilayers that is observed when the devices are biased at and above the Negative Differential Resistance threshold. Electron temperatures as obtained from the high energy tail of the spatially integrated spectra, coupled with the applied field dependence of the photon flux indicate that the emitted light is due to the inter-band recombination of impact ionised electron-hole pairs. Spatio-temporal behaviour of the light emission is also investigated in the devices with lengths varying between 100μm and 316μm. The results show the direct relationship between the domain dynamics and the light emission. The field contrast mode of a scanning electron microscope that has been used to image space-charge domains is indicative of high domain velocities in all the samples investigated.

Self-Exciting Tunnel Junction Plasmons In Resonant Tunnelling Diode

M.N.Feiginov, V.A.Volkov.

Institute of Radioengineering and Electronics, Russian Academy of Sciences, Moscow, Russia.

The current in the semiconductor tunnel structures is ordinary supposed to be homogeneous. We have considered resonant tunnelling diode (RTD) and have shown, that current vortexes can appear on the tunnel junction, when RTD is in the negative differential conductance regime. Lateral scale of the vortexes ($1/q_0$) is determined by the ratio of the conductivity of the semiconductor regions and tunnel conductance.

Consideration is carried out in the terms of tunnel junction plasmons (TJP). TJP is a special plasma excitation, localised in the vicinity of the tunnel junction, when the charge densities of opposite signs appear on the opposite sides of the junction. These charges locally screen each other, and it leads to a quasi-gapless spectrum $\omega(q)$ of TJPs running along the junction (q is the two-dimensional TJP wavevector in the plane of the junction). That is why TJP excitation have substantial effect on the response function [1] of the tunnel structure even at low frequencies. In the case of RTD, TJP can be static with non-zero $q \sim q_0$. TJPs of the kind could violate homogeneity of the voltage drop on the tunnel junction and, consequently, that of the tunnel current. To describe the final state of the system, the problem of non-linear description of TJP was formulated and solved. It is shown that a chain of non-linear current vortexes (static and dynamic) can appear in RTD with real parameters.

The work was supported partly by the Russian Foundation for Basic Research, grant 96-02-18811, and Russian National Program "Surface atomic structures", grant 95-3.1.

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Nonequlibrium Diagrams of a Single Quantum Well Laser

S. Mil'shtein and A. K. Chin*

Advanced Electronic Technology Center
EE Dept. University of Massachusetts, Lowell, MA 01854

* Microelectronics Laboratory, Polaroid Corporation, Norwood, MA 02062

Abstract

We studied the operation of a single quantum well laser, examining the tested device by Scanning Electron Microscope (SEM) working in Differential Voltage Contrast (DVC) mode. The DVC is formed when the scanning electron beam generates emission of secondary electrons. This emission changes its intensity following a dynamic profile of Quasi-Fermi Energy (QFE) across a laser structure. The quantitative measurements of QFE is based on subtracting two digitized SEM images of a laser with no bias and with bias applied across the structure. The subtraction eliminates almost all features of the morphological contrast. The resultant image is quantified by calibrating the contrast at the edges of the structure according to the applied biases. A MOCVD grown structure consists of 160nm of $In_{0.2}Ga_{0.8}As$, positioned between n and p layers of GaAs. This structure is described in detail in the paper. The specially cleaved laser structure was forward biased to get threshold and saturation of infrared emission. In various modes of operation of the laser, the in-situ DVC profiling of QFE across the device was performed. The intensity of the laser emission was simultaneously measured by a detector positioned in the SEM chamber. Starting with an equilibrium energy diagram of an unbiased tested laser, having an experimental profile of Quasi Fermi levels across the operational laser we reconstructed the complete nonequilibrium energy diagrams. Nonequilibrium energy diagrams for regimes of inverse population, threshold lasering, and saturation are presented, which helps to understand operational benefits or deficiencies of the quantum laser.

TuB Optical processes and luminescence in quantum dots

Luminescence and magneto-luminescence spectroscopy of InAs self-assembled quantum dots

P.D. Wang, J.L. Merz
Department of Electrical Engineering, University of Notre Dame, Notre Dame, IN 46556

G. Medeiros-Ribeiro, M. Oestreich, P.M. Petroff
Center for Quantized Electronic Structures (QUEST),
Materials Department, and Department of Electrical and Computer Engineering
University of California, Santa Barbara, CA 93106

H. Akiyama, H. Sakaki
Research Center for Advanced Science and Technology, University of Tokyo,
and Quantum Transition Project, Research Development Corporation of Japan,
4-6-1 Komaba, Meguro-Ku, Tokyo, Japan

Recently, the optical properties of self-assembled quantum dots (SADQs) have attracted much interest due to their potential for optoelectronics applications. Highly strained layer systems result in Stranski-Krastanow growth for which growth starts two dimensionally, but after reaching a certain critical thickness, coherent islands form spontaneously, usually connected by a "wetting layer". In the case of the In(Ga)As-Ga(Al)As system, the typical diameter of these islands is 20 nm and the height of 4 nm. Photoluminescence (PL) and photoluminecence excitation (PLE) spectroscopy reveal what appears to be a "Stokes" shift for In(Ga)As-Ga(Al)As SADQs. We demonstrate that the first two excited states observed in PLE originate from the doubly-degenerate first excited state. The splitting of its degeneracy is caused by the random potential of alloy disorder and size fluctuations. The ground state is not observed in the PLE of the quantum dot because of its sharp δ-funtion-like density of states. Our experimental data agrees very well with a recent theoretical calculation by Tsiper[1]. From the line shape change observed in PLE with applied magnetic field, we will demonstrate the importance of this random potential influence on the energy levels of the dots.

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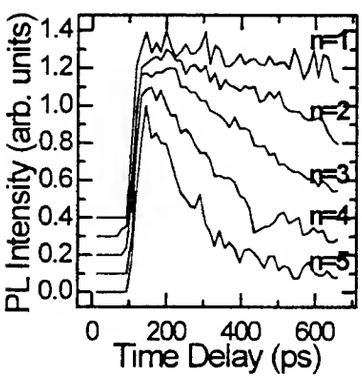
TIME-RESOLVED PHOTOLUMINESCENCE OF EXCITED STATES IN $In_{1-x}Ga_xAs/GaAs$ SELF-ASSEMBLED QUANTUM DOTS

S. Raymond[*†], S. Fafard[*], P.J. Poole[*], A. Wojs[*§], P. Hawrylak[*], S. Charbonneau[*], D. Leonard[‡], R. Leon[‡], P.M. Petroff[‡] and J.L. Merz[‡].

[*]Institute for Microstructural Sciences, National Research Council of Canada, Canada K1A 0R6
[†]University of Ottawa, Ottawa, Canada
[§]Technical University of Wroclaw, 50-370 Wroclaw, Poland
[‡]Center for Quantized Electronic Structures (QUEST) and Materials Department and Electrical and Computer Engineering Department University of California, Santa Barbara, California 93106

We have obtained large (36 nm diameter) $In_{0.5}Ga_{0.5}As/GaAs$ self-assembled dots (SADs) using the Stranski-Krastanow growth mode. In steady-state with low excitation intensity, our photoluminescence (PL) results show a single inhomogenously broadened emission line with FWHM of 40 meV. As the excitation intensity is increased, high-energy luminescence lines (up to 5 in total) progressively appear. Model calculations in the adiabatic approximation show that the PL lineshape is consistent with a system of SADs where excited state emission is caused by state-filling effects. Next, the multiple-peak spectrum is monitored as the temperature is increased in order to investigate the localization potential of the excitons. A progressive decrease of the PL intensity is observed with increasing temperature, with successive quenching of the higher-energy lines, and ground state luminescence observed up to 250K, which is consistent with a deep confinement in a 0-D potential. Finally, we measure the time-dependent PL emission of each emission line in order to confirm the state-filling dynamics of the system. Relaxation times are found to speed up as the excitation intensity is increased, and as higher energy levels are probed, thus both the CW PL and TRPL are found to be best explained in terms of state-filling effects in a 0-Dimensional structure. The figure gives an example of the TRPL traces obtained at a given excitation intensity.



Composition and Strain of Self-Assembled (In,Ga,Al)Sb/(Ga,Al)As Quantum Dots

B.R. Bennett, B.V. Shanabrook, E.R. Glaser, R. Magno, and M.E. Twigg
Naval Research Laboratory, Washington, DC 20375-5347, U.S.A.

In spite of the enormous amount of research that has been performed recently on self-assembled quantum dots (QDs) induced during Stranski-Krastanov growth, relatively little work has addressed the important parameters of chemical composition and strain. For the most part, it has been assumed that exchange reactions or segregation do not occur during the growth of the QDs. Furthermore, little is known about the impact of strain on the band alignments, energy gap, and interlevel separation of the QDs. The determination of both composition and strain are required before accurate calculations of the properties of QDs can be performed. In this work, we apply Raman spectroscopy, photoluminescence, and TEM to investigate the composition and strain of InSb, GaSb, and AlSb QDs grown by MBE on Ga(Al)As.

The chemical content of the QDs, as probed by the vibrational properties, was investigated with low-temperature Raman spectroscopy. Samples with QDs were compared to control samples which included thin layers of antimonides but no QDs. All samples exhibited GaAs LO and TO modes. A third peak is observed at 233 cm^{-1} (192 cm^{-1}) for samples with GaSb (InSb) QDs and is absent for the control samples. Because this energy is near the optical phonon branches of bulk GaSb (InSb), we attribute it to optical vibrations of the GaSb (InSb) QDs. In contrast, Raman spectra of AlSb QDs include peaks at 331 cm^{-1} and 226 cm^{-1}. We attribute these peaks to the two-mode behavior of $Al_xGa_{1-x}Sb$ QDs which results from Ga segregation into the AlSb. The low-energy (GaSb-like) peak disappears when 14 Å AlAs is inserted between the AlSb and GaAs. These results demonstrate the power of Raman spectroscopy to provide chemical information for self-assembled QDs.

Photoluminescence energies are a strong function of both composition and strain in QDs. Antimonide QDs were capped with GaAs for PL studies. (The presence of quasi-hemispherical QDs after cap deposition is obvious from the imaging of strain fields using TEM.) We observe strong emission with peak energies near 1.15 eV and FWHM $\sim$ 80 meV at 1.6 K from InSb and GaSb QDs. The PL bands from both the GaSb and InSb QDs shift to lower energy with decreasing excitation power density, in contrast to the behavior observed for InAs/GaAs QDs. This suggests a Type–II band structure with electrons in the GaAs and holes in the InSb or GaSb QDs. This work illustrates the importance of including strain effects in calculating the band structure of QDs. For example, a type-I band alignment is predicted for the InSb QD samples based on the InSb/GaAs ΔE_C and ΔE_V alone. Strain within the InSb QDs raises the InSb CB minimum above the CB edge of the adjacent GaAs layers while the holes remain confined in the InSb. Confirmation of this assignment, with electrons in the GaAs and holes in the (In,Ga,Al)Sb QDs, is found from the blue-shift of PL observed for InSb QDs embedded in $Al_{0.1}Ga_{0.9}As$.

Excited-state luminescence from vertically-stacked and electronically-coupled InAs pyramids in GaAs

Mark S. Miller, Lars Landin, Mats-Erik Pistol, Pedro Castrillo
Craig Pryor, Bernhard Kowalski, Søren Jeppesen, and Lars Samuelson

Department of Solid State Physics, Lund University, 221 00 Lund, Sweden.

Small InAs pyramids can be formed without dislocations during the initial stages of InAs growth on GaAs. The resulting conduction-band potential-well can contain only a single bound state[1], making the pyramids excellent candidates for electronic-structure building-blocks if coupled quantum mechanically. However, when laterally aligning islands on patterned substrates, we found a minimum lateral barrier near 11 nm[2], giving coupling energies less than 1 meV. When we instead vertically stacked ten islands inbetween GaAs layers, producing tip-to-base separations less than 2 nm, we obtained composit objects in a strongly-coupled regime[3]. Solomon, et at., have also reported vertically coupled pyramids in this regime[4].

Vertically coupling the InAs islands causes the low-temperature photoluminescence to shift to lower energy and to become narrower. The energy shift is due to the confined states coupling and dispersing into a miniband and to the hydrostatic strain decreasing within the stack. The 10-pyramid, 5.6 nm period sample of the present study was grown with chemical beam epitaxy. The sample shows a 27-meV-wide photoluminescence peak shifted down by 180 meV at 5 K and also luminesces at room temperature.

Here we present power-dependent PL and PLE of stacked InAs islands. The stacks band fill very easily with increasing excitation power density, beginning at a power density of 6 W/cm^2. The band filling becomes substantial near 30 W/cm^2, where the PL peak width has doubled to approximately 50 meV. For comparison, a typical quantum well sample requires on the order of 10^4 W/cm^2 to show similar bandfilling[5]. At a power giving an 88-meV-wide PL band, there are three excited-state peaks. Photoluminescence excitation spectroscopy also shows excited-state peaks, which are separated by about 20 to 40 meV. The excitation spectra also show a very strong absorption edge due to the thin InAs wetting layers the pyarmids islands sit on.

By using a simple one-dimensional model, we estimate that the pyramids have tightly-coupled conduction-band states in a 0.25 eV wide miniband. The excited states in the ten levels of this miniband thus have an average spacing of 25 meV, and are candidates for the excited states seen in our spectra. We expect the valence band electronic structure to be substantially more complicated, with the states not only coupling but also mixing due to the strain and coupling.

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Carrier Relaxation and Thermal Activation of Localized Excitons in Self-organized InAs Quantum Dots

Z.Y.Xu, Z.D.Lu, X.P.Yang, Z.L.Yuan, B.Z.Zheng, J.Z.Xu, and W.Zhang
National Laboratory for Superlattices & Microstructures, Institute of Semiconductours, Academy Sinica, Beijing 100083, China
Fax: 86-10-2562389 E-mail: trzyxu@red.semi.ac.cn

W.K.Ge, Y.Wang, J.Wang, and L.L.Chang
Department of Physics, Hong Kong University of Science & Technology, Clear Water Bay, Kowloon, Hong Kong

We have investigated the temperature dependence of photoluminescence (PL) properties for a number of self-organized InAs/GaAs heterostructures with InAs layer thickness ranging from 0.5 monolayer (ML) to 3 ML. The temperature dependencies of InAs exciton emission energy and line-width were found to display a significant difference when the InAs layer thickness is smaller or larger than the critical thickness ~1.7 ML. While InAs monolayer and submonolayer presented similar behaviors as a 2D system, InAs multilayers showed unusual temperature dependence of PL properties: a fast red-shift of PL energy and an anomalous decrease of line-width with increasing temperature. We believe that this unusual temperature dependence is a typical characteristic of self-organized InAs QDs, resulting from the enhanced carrier relaxation process due to the overlap of the wave functions of carriers in InAs coupled quantum dots with size fluctuation.

By plotting $\log(I_{PL})$ vs $1/kT$ we have obtained the thermal activation energies of 27, 64, 110, and 130 meV for 0.5, 1, 2.5, and 3 ML InAs, respectively. These values are comparable to the corresponding energy differences between GaAs and InAs in 0.5 and 1 ML samples, and to those between InAs QDs and wetting layer for the latter two samples. Our results suggest that the potential barriers for InAs excitons thermally out of the localized states are different. For a high quality InAs multilayer the InAs wetting layer could be acted as a barrier for the thermionic emission of carriers, while in InAs monolayers and submonolayers the carriers are required to overcome the GaAs barrier to thermally escape from the localized states.

Radiation Characteristics of Injection Lasers Based on Vertically Coupled Quantum Dots

S.V.Zaitsev, N.Yu.Gordeev, Yu.M.Sherniakov, V.M.Ustinov, A.E.Zhukov, A.Yu.Egorov, N.N.Ledentsov, M.V.Maximov, D.Bimberg*, P.S.Kop'ev, and Zh.I.Alferov

A.F.Ioffe Physical-Technical Institute of the Russian Academy of Sciences,
Politekhnicheskaya 26, 194021, St.-Petersburg, Russia
*Institut fur Festkorperphysik, Technische Universitat Berlin,
Hardenbergstr. 36, D-10623 Berlin, Germany

It was shown that InGaAs quantum dot (QD) lasers grown by MBE can show extremely high temperature stability (T_o ~ 350K) in a wide temperature range up to 150K. This value exceeds theoretical limit for quantum well (QW) lasers [1]. However, at RT most of electroluminescent properties of the lasers were limited by the delocalization of nonequilibrium carriers from QD states. Characteristic temperature To at the range of 300K dramatically decreased down to 60K, and maximum total gain achieved was only about 70 cm^{-1}. In the present work we show that when the number of QD sheets in an active layer of injection laser is increased, the threshold current density gradually decreases, total gain increases and lasing through QD states show no saturation in wide range of pumping current densities.

While for N=1 threshold current was as high as 900A/cm^2, for N=3 it was only 360A/cm^2, and for N=6 and 10 it was equal to 220 and 90A/cm^2, respectively.

The maximum gain increased about 6 times and reached more than 400cm^{-1}. However, due to the interaction of quantum dot states and minizones formation, To value decreased at low temperatures. At the same time RT temperature stability increased to 150K for N=10. Threshold current density as low as 18A/cm^2 at 85K was achieved for stripe geometry laser made from this heterostructure.

Spectral investigations show that while lasing through QD states saturates at about 2.5kA/cm^2 for N=3, for N=6 and 10 such a saturation was not observed at least up to 3.5kA/cm^2.

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TuC Magnetotransport in mesoscopic systems

QUANTIZATION AND CONFINEMENT PHENOMENA IN SUPERCONDUCTING MICROSTRUCTURES AND SUPERLATTICES*

V.V. Moshchalkov#

Laboratorium voor Vaste-Stoffysika en Magnetisme, Katholieke Universiteit Leuven, Celestijnenlaan 200D, B-3001 Leuven (Belgium).

We have studied flux line confinement by artificial regular arrays of submicron holes ("antidots") in superconducting single layers (Pb,WGe) and multilayers (Pb/Ge, WGe/Ge). Magnetization $M(T,H)$, critical current density $j_c(T,H)$, and pinning force f_p have been measured as a function of field H and temperature T in films with triangular and square lattices of antidots with different radii, r. Due to efficiency of antidots as pinning centers, $J_c(T,H)$ and f_p are very strongly enhanced. Besides an overall j_c enhancement distinct anomalies are observed exactly at expected matching fields H_m corresponding to an integer number of flux lines (FL) per antidot lattice unit cell. In dependence upon the r value and applied field, antidot lattices can stabilize both multi-quanta vortices at antidots and single-quantum vortices at interstices. For relatively small r, antidots pin only single-quantum flux lines (FL) and other FLs are forced to be "caged" at interstices. The interstitial FLs have much higher mobility than that of FLs pinned by antidots [1]. For larger antidots and temperatures not very far from T_c multi-quanta vortex lattices are formed, thus realizing a novel "single-terrace" critical state corresponding to a flat field profile. The cusp-like $M(H)$ anomalies appearing at $H = H_m$ and logarithmic behavior $M \propto -\ln(H-H_m)$ between the matching fields are successfully described by the simple expression derived for interacting multi-quanta vortices in the London limit. Finally, new perspectives for the "quantum design" of superconducting critical parameters (j_c, f_p, etc.) through nanostructuring are also discussed.

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STEP-LIKE MESOSCOPIC CONDUCTANCE IN INHOMOGENEOUS MAGNETIC FIELDS

Yuli Lyanda-Geller[a] **Paul M. Goldbart**[b,c,a] **and Daniel Loss**[d]
[a] *Beckman Institute,* [b] *Department of Physics, and* [c] *Materials Research Laboratory*
University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, U.S.A.
[d] *Department of Physics, Simon Fraser University, Burnaby, B.C. V5A 1S6, Canada*

Inhomogeneous magnetic fields (textures) lead to interference effects in conductors that are similar to those caused by Aharonov-Bohm fluxes. The origin of these effects is the geometric (i.e. Berry) phase acquired by the electron wavefunction as the electron orbits, its spin thereby encountering an adiabatically varying magnetic field. The acquired phase is characterized by the solid angle subtended by the magnetic field as the electron propagates.

Textures can be created experimentally in several ways, including certain arrangements of current-carrying (possibly superconducting) wires, magnetic atomic force microscopy, or the deposition of ferromagnetic or type II superconducting materials on top of a two-dimensional electron gas (2DEG). In yet another option, one makes use of intrinsic spin-orbit splitting in semiconductor heterostructures to create an effective inhomogeneous Zeeman field.

In this paper we address the conductance of rings confined to the 2DEG. If, for example, the texture is such that the field rotates through 2π as the ring is circumnavigated then the phase acquired by the orbiting electron would be π. This would manifest itself in the ballistic conductance of the ring, as it would produce a phase shift between electrons moving on the different branches. If an additional, homogeneous, in-plane magnetic field B_h is applied then, provided $B_h < B_t$ (where B_t is the magnitude of the texture), interference modulation (due to the π phase shift) occurs. This modulation abruptly disappears for $B_h > B_t$. As this effect relies on the ballistic nature of the propagation, and therefore requires very large magnetic fields to validate adiabaticity (and consequently the use of the geometric phase), its experimental realization is not easy. However, adiabaticity can readily be satisfied if the ring is disordered, so that the electron motion is diffusive: the electron remains longer in regions in which the magnetic field is essentially uniform, and its spin can adjust to the local direction of the field.

We therefore consider mesoscopic rings and focus on conductance fluctuations. We show that the conductance correlator $\langle g(B)\, g(B+\delta B)\rangle - \langle g(B)\rangle \langle g(B+\delta B)\rangle$ has a step-like form: for B_h and $B_h+\delta B$ either both smaller or both larger than B_t, the correlator has essentially the same value; when these conditions are violated, the correlator abruptly changes to another (essentially constant) value. For B_h and $B_h + \delta B$ both smaller than B_t, the same phase π characterizes the modulation of the conductance at B and $B + \delta B$. Similarly, for B_h and $B_h + \delta B$ both larger than B_t, modulation of the conductance is absent at both B and $B + \delta B$. On the other hand, in the intermediate situation (i.e. $B_h < B_t$ and $B_h + \delta B > B_t$) modulation of the conductance differs at B and $B + \delta B$ and, correspondingly, the correlator takes on a new value. Along the way, we shall see that transitions of this type are absent in the weak localization regime, but do occur in conductance fluctuations, albeit for Zeeman but not spin-orbit textures.

We conclude that experiments such as those described here, involving in-plane magnetic fields, have the potential to provide unambiguous observations of Berry phases in the setting of electronic transport.

UNIVERSAL CONDUCTANCE FLUCTUATIONS IN A RANDOM MAGNETIC FIELD.

G.M. Gusev,[1] X. Kleber,[2,3] U. Gennser,[4] D.K. Maude,[2] J.C. Portal,[2,3]
D.I. Lubyshev,[1] P. Basmaji,[1] M. P.A. da Silva,[1] J.C. Rossi,[5]
and Yu.V. Nastaushev.[6]

[1]Instituto de Fisica de São Carlos, 13560-970, Universidade de São Paulo, SP, Brazil
[2]CNRS-LCMI, F-38042, Grenoble, France
[3]INSA-Toulouse, 31077, France
[4]Paul Scherrer Institute, CH-5232 Villigen-PSI, Switzerland
[5]Universidade Federal de São Carlos, Brazil
[6]Institute of Semiconductor Physics, Russian Academy of Sciences, Siberian Branch, Novosibirsk, Russia

The localisation problem for a two-dimensional electron gas (2DEG) experiencing a random magnetic field has recently attracted considerable interest. The motivation stems from the theoretical prediction, that in the regime of the fractional quantum Hall effect, at filling factor 1/2, composite fermion quasi-particles move in a static random effective magnetic field. Electrons confined to a non-planar, "dimpled" GaAs/AlGaAs heterojunction experience a random magnetic field B [1]. Since the 2D electrons are sensitive only to the normal component of B, they will move in an inhomogeneous (B perpendicular to the substrate ($B_\perp$)) or sign-alternating, "tiled" magnetic field (when B is parallel to the substrate ($B_\parallel$)). In this work universal conductance fluctuations (UCF) at the scale of e^2/h were measured in small structures (2μm × 2μm). The effects on the conductance fluctuations on the angle Θ between the field and the normal of the substrate plane were studied using an in situ rotation of the sample. It is found, that fluctuations of two magnetoresistance curves are completely uncorrelated if the difference in Θ is > 15°- 20°. According to UCF theory interference between electron trajectories are destroyed, when flux through an area $L_\varphi b$ is in order of unity (L_φ is phase relaxation length and b is the height of the dimples). It gives the value of correlation angle $\Theta_c = \Phi_0 d / L_\varphi b^2 B = 0.3$ rad, with the parameters d (periodicity of dimples) and b deduced from a scanning electron picture of the sample, in agreement with the experimental value. Thus, the correlation properties of the observed UCF give information about the topology of the non planar 2DEG.

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MAGNETOMETRY OF MESOSCOPIC SUPERCONDUCTORS

A.K.Geim

University of Nijmegen, 6525 ED Nijmegen, The Netherlands

Experimental access to mesoscopic metal and semiconductor samples has brought about a whole wealth of new physical phenomena. At the same time, other mesoscopic systems, e.g. mesoscopic superconductors have received little attention so far, probably because conventional transport measurements can provide information only about the onset of superconductivity and do not allow probing in the superconducting state.

In this context, we have developed a novel micromagnetisation technique which allows non-invasive access to properties of submicron and even nanometer-sized objects of virtually any desired form and material in a very wide range of temperatures and magnetic fields. The technique is based on detection of a local magnetic field by submicron Hall probes and its present sensitivity is already better than 10^6 μ_B. In several regimes, including mesoscopic superconductors, our approach has essential advantages over possible alternative techniques such as μ-SQUIDs and μ-mechanical cantilevers.

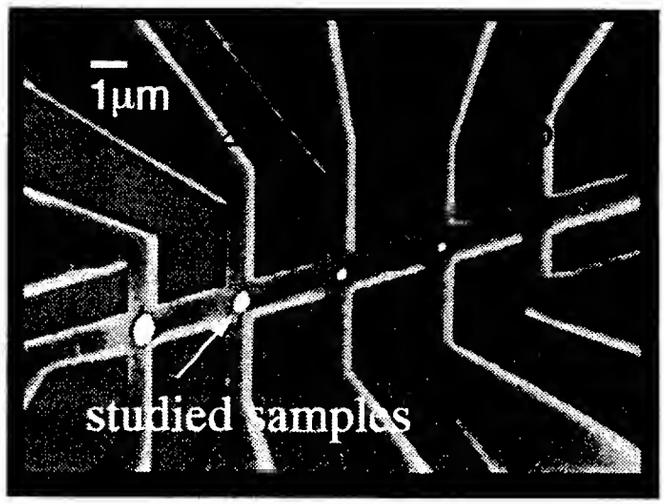


Figure. SEM micrograph of one of our devices.

To demonstrate the ability of the new method, I will describe magnetisation studies of individual submicron superconducting samples. The experiment reveals a number of new, unexpected features related to the reduced dimensionality and large surface-to-volume ratio, e.g. a) the first order phase transition due to quantization in the superconducting energy spectrum and b) a mesoscopic correction to the ideal Meissner state.

papers per title

LOW-FIELD MAGNETORESISTANCE OF STRONGLY MODULATED TWO-DIMENSIONAL ELECTRON GAS

P. Středa and J. Kučera

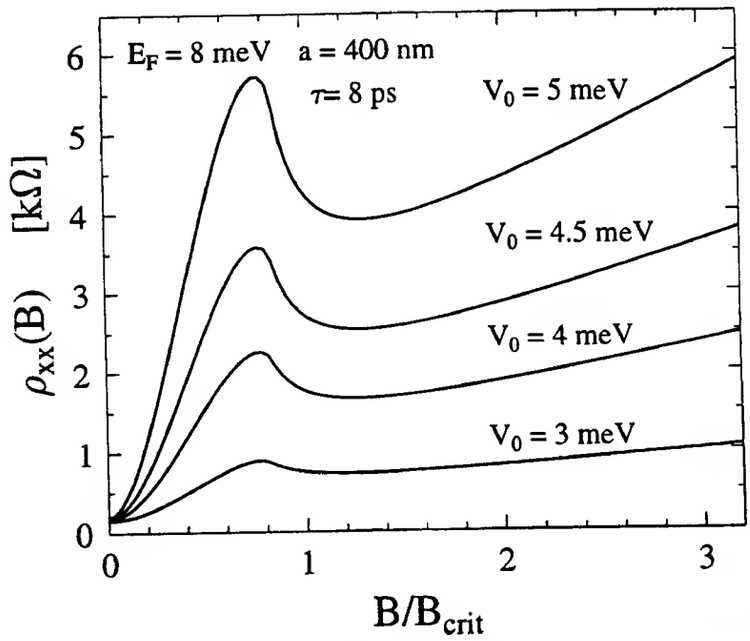
Institute of Physics, Academy of Sciences of the Czech Republic

Cukrovarnická 10, CZ-162 00 Praha

Imposing a one-dimensional periodic potential upon a two-dimensional electron gas creates a lateral superlattice with peculiar transport properties. Accept of commensurability oscillations the magnetoresistance peaks at low magnetic fields are observed. It is generally accepted that this effect is due to the presence of open electron trajectories and their gradual breakdown induced by Lorenz force. Beton et. al. [1] have found that peak positions scale with $B_{crit} \sim V_0/v_F a$ for which the number of open trajectories vanishes. Although their treatment gives proper scaling with the period a and amplitude V_0 of the potential modulation the predicted rapid fall of the resistance at $B > B_{crit}$ was not observed.

To describe the low-field magnetoresistance we have followed the already described procedure [2], which was generalized for the case of strongly modulated systems. Electrons are considered to be classical particles with well defined trajectories which satisfy the equation of motion and with expectation velocity values defined by zero field energy spectra. To establish the conductivity uniform relaxation time τ is assumed and the Chambers solution of the linearized Boltzmann equation is used.

We have found that total magnetic breakdown never occurs and although the number of persisting open trajectories decreases with rising magnetic field their effect to the electronic transport is strengthen for $\omega_c\tau > \pi$ (ω_c is the cyclotron frequency). As the result magnetoresistance peaks are followed by the resistance increase at higher magnetic fields.



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EXCITON SPECTRA OF $Pb_{1-x}Mn_xI_2$ MICROCRYSTALS

A.I.Savchuk, S.V.Medynskiy, I.D.Stolyarchuk, P.I.Nikitin*

Dept.Phys.Electronics, State University, Chernivtsi,274012,Ukraine

***General Physics Institute, Moscow, 117942, Russia**

Lead diiodide - transition metal diiodide systems are formed a new group of semimagnetic semiconductors. On the other hand, they belong to typical layered crystals and are very attractive for study of confinement effect in ultrathin layers. In addition, our previous paper has demonstrated clear confinement effect on excitons in $Pb_{1-x}Mn_xI_2$ microcrystals [1]. In this communication we present new results of exciton spectra for these zero-dimensional structures.

The samples of $Pb_{1-x}Mn_xI_2$ microcrystals with x = 0.01;0.05;0.08;0.1 have been grown by embedding into polyvinylalcohol and gelatin matrices. Average size of small semiconductor particles was controlled by choosing of conditions for growth and subsequent heat treatment. High resolution transmission electron microscopy investigations have shown that the obtained microcrystals are platelet-like in contrary to spherical shape of $A^{II}B^{VI}$ microcrystals. Measurements of optical absorption and photoluminescence spectra were carried out with temperature ranging from 4.2 to 300 K.

The most important results obtained in these studies are the following. The main exciton absorption band for microcrystals in polyvinylalcohol are shifted toward short wavelengths as compared with that of bulk crystal. The same behaviour was found for photoluminescence band which is associated with the free exciton emission. It was found that value of shift increased with decreasing particle thickness. Besides, new absorption bands were observed for microcrystals embedded in gelatin matrix. In accordance with recent results for PbI_2 microcrystals [2] these exciton peaks correspond to the discrete thickness of particles which include finite number of layers. From temperature dependence of exciton structure in absorption spectra, the evidence for modification of interaction between excitons and phonons in semimagnetic semiconductor microcrystals is obtained.

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A study of the electron scattering by optical phonons in semiconductor heterostructures.

X Zianni, C D Simserides and G P Triberis.

University of Athens, Department of Physics, Section of Solid State Physics, Zografou 157 84, Athens, Greece.

The scattering of a quasi two dimensional electron gas by optical phonons in selectively doped AlGaAs\GaAs\AlGaAs heterostructures is systematically studied in order to examine the effect of phonon confinement. The electron states are calculated self-consistently so that an accurate dependence upon the structure parameters and the temperature is considered [1]. The quasi two dimensional phonon modes are given by a macroscopic model that includes bulk dispersion and both electrostatic and mechanical boundary conditions [2]. This model has been found to agree very well with reliable microscopic models [3]. The relaxation times for the electron subbands are calculated by solving the system of Boltzmann equations iteratively. The effect of temperature and well width variation is studied. The results are compared with experimental results.

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INCOMMENSURABILITY OF THE ONE-DIMENSIONAL SYSTEMS STABILIZED IN THE NANOCHANNEL MATRICES

V.V.Poborchii, A.N.Efimov

Ioffe Physico-Technical Institute, St.Petersburg 194021, Russia

Recently a number of semiconducting materials has been incorporated into the channels of microporous matrices such as chrysotile asbestos and zeolites and one-dimensional systems (quantum wires and chains) has been realized. The systems display many interesting structural, vibrational, and electronic properties. One of the fundamental properties of this kind of systems is the incommensurability between the lattice parameter of the incorporated material and that of the matrix. If the energy of the interaction between the atoms in the one-dimensional system is comparable with the energy of the interaction between the one-dimensional system and the matrix, one can expect observation of the structural changes in the system depending on the temperature and other parameters.

We present experimental results on the dramatic temperature dependent structural changes of the Se chain stabilized in the cancrinite matrix. Se atoms organize dimerized linear chains in the cancrinite channels, and the structural changes are attributed to the change of the ordering of the dimers in the chain. We consider these changes as a result of the incommensurability between the lattice parameters of the chain and matrix. This point of view is supported by the molecular dynamics simulation of the temperature dependence of the structure and vibrational spectrum of the dimerized linear chain under the influence of the periodic incommensurate potential.

GIANT DIELECTRIC CONSTANT AND PHASE TRANSITIONS OF THE REGULAR ARRAY OF SODIUM NITRITE PARTICLES IN THE OPAL MICROCAVITIES

S.V.Pan'kova[a], V.V.Poborchii[b], V.G.Solov'ev[a], S.M.Samoilovich[c]

[a] Pskov State Pedagogical Institute, Pskov 180760, Russia

[b] Ioffe Physico-Technical Institute, St.Petersburg 194021, Russia

[c] Moscow State University, Moscow 119899, Russia

Ordered systems of ferroelectric nanoparticles possess many interesting physical properties depending on the characteristic sizes of particles. In this work the regular array of sodium nitrite nanoparticles has been fabricated in the opal matrix by imbibition of synthetic opal specimens in the sodium nitrite melt at 550-560 K. Linear sizes of the ferroelectric guest nanoparticles have been conditioned by the diameters of silica spheres (~200nm) closely packed in the cubic face-centered host matrix structure. The capacitance of the specimens was measured by at the frequencies 1 kHz and 100 Hz in the temperature interval from 300 to 600 K.

Dielectric behavior of the prepared composite material displays features associated with the ferroelectric and melting-freezing phase transitions in the sodium nitrite nanoparticles. A low temperature shift ~10 K of the Curie point (compared to that of the bulk $NaNO_2$) was found at cooling, and considerable broadening (up to 100 K) of the melting-freezing phase transition was observed. A giant dielectric constant (up to 10^8 at 100 Hz) was obtained at high temperatures, when the sodium nitrite particles transform to the electrolytic drops during the melting process.

MANY-BODY EFFECTS IN THE OPTICAL PROPERTIES OF ZnCdSe-ZnSe QUANTUM WELL STRUCTURES

F.P. Logue, J.F. Heffernan, P. Rees, C. Jordan, J.F. Donegan, J. Hegarty, S. Tanaguchi*, T. Hino*, F. Hiei*, and A Ishibashi*

Physics Department, Trinity College, Dublin 2, Ireland

Tel: +353-1-608 2169, Fax: +353-1-679 8412, Email fplogue@tcd.ie

*Sony Research Centre, Fujitsuka-cho 174, Hodogaya-ku, Yokohama-shi 240, Japan

The recent announcement of a blue-green diode laser with a room temperature operating lifetime in excess of 100 hours has provoked renewed interest in the physics of II-VI semiconductor materials for optical emitters. The Coulomb interaction in a wide band gap semiconductors is considerably stronger than in narrow gap III-V materials and this has led to speculation that excitonic effects contribute significantly to the room temperature optical properties if II-VI quantum wells.

We have measured gain spectra from optically pumped 40Å ZnCdSe-ZnSe quantum wells over a range of temperatures and intensities. Comparison with a many body calculation indicates that gain arises from a Coulomb enhanced electron hole plasma at room temperature and hat excitonic effects are not significant, for temperatures higher than 100K. The effect of Coulomb enhancement on the gain in these samples is pronounced and this has important consequences for optical emitters based on II-VI materials.

Coulomb enhancement also effects spontaneous emission rates in these structures. At room temperature, we observe very long carrier lifetimes, up to 3ns, for he first time in these materials indicating the excellent quality now possible. We find that at low carrier densities the spontaneous emission rate is enhanced by up to 40% while at higher densities the Coulomb enhancement is reduced and the lifetime approaches 1ns, in agreement with our experimental results.

This work is in part supported by the Sony Sabbatical Chair Program.

FIELD-INDUCED LOCALIZATION PROCESS IN THE NATURAL SUPERLATTICE OF SILICON CARBIDE POLYTYPES: FROM BLOCH OSCILLATIONS TO ELECTRICAL BREAKDOWN.

V.I.Sankin, I.A.Stolichnov

A.F.Ioffe Physico-Technical Institute, St.-Petersburg, Russia

Hexagonal polytypes of silicon carbide (SiC) are a semiconductors with natural superlattice which determine many physical phenomena in a crystals of these polytypes. In the first place these are the phenomena in the strong electric field. In this study we deal with different manifestations of the field-induced localization (FIL) process. The electric fields in which FIL process is observed ranges from several hundreds kV/cm for Bloch oscillations to several thousands kV/cm for the impact ionization and electrical breakdown [1] and directed along the natural superlattice axis. The process of WSL development was studied experimentally on a number of SiC polytypes with different superlattice parameters. Such important phenomena as negative differential conduction due to the Bragg reflection of electrons, phonon-assisted hopping in Wannier-Stark ladder system, full localization of the first miniband and resonant interminiband tunneling [2] discovered in the investigation is a subject of discussion in this paper. Besides we present the results of the study of FIL influence on impact ionization and electrical breakdown in SiC crystal and discuss the mechanism of electron heating in miniband spectrum condition.

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HOT ELECTRON SURFACE EMITTER

TYPE I

A. O'Brien and N. Balkan
University of Essex, Department of Physics, Wivenhoe Park,
Colchester, Essex, CO4 3SQ, United Kingdom

Hot Electron Light emission and Lasing in Semiconductor Heterostructures (HELLISH) type I is a novel surface emitting device which consists of a $Ga_{1-x}Al_xAs$ p-n junction containing a *GaAs* quantum well on the n-side of the depletion layer. This device utilises longitudinal transport mechanisms which enables heating of electrons and holes with application of electric fields parallel to the layers. Hot electrons and holes are captured by tunnelling and thermionic emission in the quantum well where radiative recombination occurs. A demonstration of the device operation is presented using photoluminescence and electroluminescence techniques. It is shown that light emission is independent of the polarity of the applied bias. The application of the device as an XOR and NAND gate has been demonstrated. A novel hot electron vertical cavity laser (HELLISH-VCSEL) is also proposed.

RESISTANCE RESONANCE EFFECTS IN THE PHOTOCONDUCTIVITY OF Si PLANAR-DOPED GaAs/AlGaAs HETEROSTRUCTURES*

M. S. C. MAZZONI, A. T. G. CARVALHO, A. G. OLIVEIRA, H. CHACHAM
Departamento de Física, ICEx, Universidade Federal de Minas Gerais
Caixa Postal 702, Belo Horizonte, 30161, Brazil

Epitaxial techniques such as MBE and CBE permit the growth of heterostructures with parallel conduction channels separated by a few nanometers [1]. If the electron mobilities of these channels are different, it is possible to observe a resistance resonance effect [2] by applying an electric field perpendicular to the plane of the conduction channels. This effect is characterized by a resistivity enhancement caused by the delocalization of the electron wavefunction among the channels.

In the present work we show that the resistance resonance effect is responsible for an anomaly in the persistent photoconductivity of MBE-grown GaAs/AlGaAs heterostructures with a Si planar-doped layer at the AlGaAs side, near the interface. The anomaly is characterized by a minimum in the photoconductivity as a function of the light dosage. We perform self-consistent calculations, in the effective mass approximation, that show that the minimum in the photoconductivity originates from an internal electric field caused by the ionization of Si impurities at the planar-doped region. For a certain value of this internal electric field, (which corresponds to a given light dosage) the electron wavefunction of the second and third sub-bands become delocalized among two channels, one at the interface and the other at the planar-doped region. Under these conditions the resistance resonance effect occurs due to the difference in the electron mobility of the two channels.

We also perform calculations for the conductivity of the samples as a function of the electron Hall density (for a cumulative light dosage) with a three-parameter model that uses the self-consistent wavefunctions as input. The model permits a quantitative fit to the experiment and indicates that the existence of a minimum in the photoconductivity depends not only on the resistance resonance effect, but also on the mobility ratio among the sub-bands. This explains the fact that the photoconductivity minimum is only observed at selected samples.

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The Optical Absorption of Type-II Superlattices

S. Glutsch[1,2] and D.S. Chemla[2]

[1]*Friedrich-Schiller-Universität Jena, Institut für Festkörpertheorie und Theoretische Optik*

[2]*Department of Physics, University of California at Berkeley*
and Material Sciences Division, Lawrence Berkeley National Laboratory

For the first time, spectra of type-II superlattices are calculated, including all miniband transitions, Coulomb interaction, and continuum states. By comparison of the optical spectra with the miniband structure and the optical density of states, we identify th optical transition which contribute to the absorption spectrum. We observe that the optical absorption of type-II superlattices is dominated by intersubband transitions which are forbidden in the type-I case. On the other hand, allowed optical transitions in type-I superlattices may become invisible in type-II structures.

By gradually increasing the modulations of the band edge, we perform transitions from a bulk semiconductor to a type-I superlattice and from a bulk semiconductor to a type-II superlattice. In the limit of infinite barrier heights, the spectrum of the type-I structure goes over in that of decoupled quantum wells. There is no such limit for type-II superlattices: as the barrier height increases, the absorption maximum perpetually moves to higher-order subband transitions.

Finally, we consider the case when a magnetic field is applied in growth direction. Then the in-plane motion of the excitons is quantized so that the one-dimensional optical density of states in the growth direction is exposed. This allowes us to clearly distinguish between a type-I and a type-II semiconductor. A pronounced Fano effect, as has been found for magnetoexcitons in bulk semiconductors, is observed only if a higher-order magnetoexciton energetically overlaps with continuum states of the same miniband transition.

Influence of internal field dynamics on Bloch oscillations in biased superlattices

G.C. Cho, A. Ziebell, T. Dekorsy, H.J. Bakker, A. Kohl, B. Opitz, and H. Kurz
Institut fur Halbleitertechnik, RWTH Aachen, D-52056 Aachen, Germany

Bloch oscillations (BO) are the most fascinating phenomena among coherent carrier transport in electrically biased semiconductor superlattice. Up to now they have been studied in AlGaAs/GaAs systems by different nonlinear optical techniques in time domain. The absorption saturation related to the nonstationary superposition of the excited carrier wavefunctions, however, can be utilized to observe the intraband carrier dynamics of Bloch oscillations based on Pauli blocking. In addition, from transmission spectroscopy data detailed information on the field dynamics can be obtained by time-resolved electromodulation experiments. Thus, in transmission spectroscopy the Bloch charge oscillation can be traced in transient electroabsorption changes. Here, we investigate time-resolved electroabsorption associated with BO in biased InGaAsP/InGaAsP superlattices by pump-probe transmission technique. We use a fs-optical parametric oscillator for resonant excitation of Wannier-Stark states and an edge state formed by arsenic interdiffusion. The intraband dynamics of the nonstationary Bloch wavepackets and their coupling to the edge state is observed. Special emphasis is paid to the investigation of the screening of the external field by the accumulation of photo-excited carriers in the superlattice embedded in a PIN-diode. The screening is measured by a time-resolved differential electroabsorption and agrees well with cw absorption data, when we compare the field-dependent absorption coefficient and the Bloch frequency in dependence of the bias voltages. As a result of the cw screening, we find a decrease of Bloch frequency with increasing excitation density at a given bias voltage. By comparison of the differential transmission with the differential electroabsorption, we show that the contribution of Pauli blocking is larger than the electro-modulation associated with the coherent wavepacket oscillations.

"High Field Transport in δ-Doped n-i-p-i Structures"

J. Heber, M. Peter, S. Eckl, S. Malzer, and G.H. Döhler
Institut für Technische Physik, Universität Erlangen-Nürnberg, Germany

A. Förster, H. Lüth
Institut für Schicht- und Ionentechnik, Forschungszentrum Jülich, Germany

We have investigated electron transport normal to the layers in a δ-doped GaAs n-i-p-i structure with excess donor density in the n-layers ("n-type n-i-p-i"). The 10-period structure was sandwiched between highly n-doped contact layers.

The system differs from the structures used for the investigation of miniband transport in a compositional superlattice structure by a much larger period (40 nm) and a barrier which is higher (about 450 meV) and triangularly shaped. Therefore, direct tunneling and thermally assisted tunneling through the barrier are expected to represent the transport mechanisms, whereas intra- and inter-miniband transport should not contribute significantly to the current. In fact, the observed current increases about exponentially over many orders of magnitude with temperature and applied voltage, in good agreement with a simple semi-classical model assuming a field dependent barrier. In addition, the current voltage curves exhibit a steep increase of the current at a critical voltage for which the first excited subband gets populated, according to our self-consistent calculations.

Our interpretation that this subband represents an additional and very efficient channel for electron transmission through the barrier is supported by the strong temperature dependence between 2 K and about 80 K resulting in a strong increase for voltages below and a strong decrease above this critical voltage. Recently we have even observed an instability which develops systematically and reproducibly from a single step at 2 K into a multistable quasi-plateau pattern which widens with increasing temperature. The fact, that these structures are not obscured by the potential fluctuations associated with the random distribution of the impurities within the doping layers (unlike the situation for n-i-p-i luminescence,e.g.) can be explained by the extreme anisotropy of the envelope wave function of the first excited state whose center of mass is situated about at the middle position between donor and acceptor layers at these high fields.

Polarization dependence of the two-dimensional Franz-Keldysh effect in MQW structures

A. Thränhardt, M. Kneissl, N. Linder, P. Kiesel, G.H. Döhler

Institut für Technische Physik, Universität Erlangen-Nürnberg, Erwin-Rommel-Str.1, D-91058 Erlangen, Germany

Recently we have demonstrated that the two-dimensional Franz-Keldysh effect is extremely appealing for applications in electrooptic modulator devices[1]. In such devices an electric field is applied in the plane of a multiple quantum well (MQW) structure. At zero field strong excitonic resonances in the absorption spectra are observed even at room temperature due to the enhanced exciton binding energies. Because of lacking in-plane confinement low electric fields are sufficient to ionize the exciton, resulting in large absorption changes at the exciton peak wavelength. If the electric field is further increased, the excitonic resonances finally evolve into the first maximum of the Franz-Keldysh oscillations and an increasing Franz-Keldysh absorption tail below the bandgap is observed. Large absorption changes of 10000 cm^{-1} in the GaAs/AlGaAs system, with an electric field of 10 kV/cm have been achieved.

Our previous results have been obtained for unpolarized light. The application of an electric field, however, breaks the in-plane symmetry of the system. Therefore, a polarization dependence of the electroabsorption is expected, resulting from a field-dependent mixing of the heavy and light hole states. We have investigated this effect on GaAs/AlGaAs (operating wavelength $\lambda \approx 850$ nm) and pseudomorphically strained InGaAs/GaAs ($\lambda \approx 980$ nm) systems. In the latter, the uppermost heavy hole and light hole states are strongly separated and the hh-lh mixing is expected to be small in the vicinity of the hh exciton peak. We actually observe a weak polarization dependence in this energy range, which increases as the energy approaches the lowest lh transition. On the other hand in the GaAs/AlGaAs MQW the separation of hh and lh transitions is small and the polarization is less dependent on the photon energy.

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LIGHT EMISSION OF SEMICONDUCTOR NANOSTRUCTURES DISTRIBUTED IN 3 - DIMENSIONAL GRATINGS

S.G. Romanov, A.V. Fokin, V.Y. Butko
Ioffe Physical Technical Institute, Polytekhnicheskaya St.,26,194021, St. Petersburg, Russia
N.P. Johnson, C.M. Sotomayor Torres
Department of Electronics & Electrical Engineering, University of Glasgow,
Glasgow G12 8QQ, UK
H.M. Yates, M.E. Pemble
Department of Chemistry & Applied Chemistry, Salford University, Manchester, M5 4WT, UK

The emission spectrum from semiconducting nanostructures embedded in a 3 dimensional grating with a spacing matching the emission wavelength has been investigated. The solid state grating causes a non-dissipative transformation of the semiconductor emission. A synthetic form of precious opal was used as a template to guide the size and spatial arrangement of nanostructures in its voids.

Opal is a fcc arrangement of identical silica balls with diameters from 150 to 350 nm. A low refractive index contrast between silica and air gives the opal a 'semi-metallic' photonic band structure. Its transmission spectrum as a function of energy T(E), demonstrates a minimum in the visible (if ball diameter falls between 170 and 250 nm) due to the destructive interference of Bragg reflected waves. The position of T(E) minimum depends on the ball diameter and angle of incident light. The half-width is around 0.2 eV, but for polycrystalline opal this minimum is replaced by a transmission edge.

Photoluminescence (PL) spectra of opal embedded semiconductors (InP, CdS, CdSe) demonstrate a maximum in the vicinity of interband absorption. The PL appears as a separate band if its position matches the stop-band of the grating, otherwise this PL smears out. In spite of different positions of PL maxima from 1.6 to 2.3 eV, their half- width is near 0.15 eV, which matches the half-width of the T(E) minimum. For lightly loaded opal (less than 1% volume fraction) the position of InP PL band corresponds to emission from nanocrystals of 10-30 nm size and does not depend upon loading. The PL from unloaded opals also shows a strong dependence upon the grating spacing. In contrast, heavy loading (i) shifts the absorption edge of InP (and CdSe) towards its bulk value, which is below the wavelength of visible light and (ii) increases absorption near the semiconductor gap. The latter prevents light propagation through the lattice and the PL becomes a surface process with no contribution from the grating environment.

The average refractive index of the opal grating (n=1.45) can be changed by coating the voids surface with a rutile layer (n=2.3), this shifts the transmission minimum towards the red for a given spacing. By maintaining the matching condition over a wider range, and increasing the semiconductor loading which makes the infill more conducting, this should allow the demonstration of electroluminescence in these composites.

OPTICAL SPECTROSCOPY OF GaAs/$Al_xGa_{1-x}As$ ASYMMETRIC COUPLED QUANTUM WELL DOTS

A. Song, G. E. Philipp, C.M. Sotomayor Torres, Y.S.Tang, C.Guasch, B.Vögele and M.C. Holland

Nanoelectronics Research Centre, Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8QQ, Britain,

Research into semiconductor nanostructures such as quantum wires and dots has been very active from both fundamental and applied perspectives. For reactive ion etched GaAs/$Al_xGa_{1-x}As$ nanostructures, process-induced damage and defects remain a problem for structures with lateral sizes less than 100nm due to the formation of a process related 'dead' layer on the sidewalls. In this work, GaAs/$Al_{0.3}Ga_{0.7}As$ coupled quantum dots from 50nm to 200nm diameter were fabricated and studied by photoreflectance and photoluminescence.

Free-standing quantum dots were fabricated by state-of-the-art electron beam lithography and reactive ion etching from a MBE grown GaAs/$Al_{0.3}Ga_{0.7}As$ p-i-n wafer containing 7 periods of coupled asymmetric double wells in the i-layer. The two quantum wells are 6nm and 12nm, respectively, separated by a 2.7nm $Al_{0.3}Ga_{0.7}As$ barrier. The surface morphology and etched depth of the dots were then examined by SEM.

Two well-defined transitions originating from the splitting hole states were detected in the dots both blue shifted by about 20meV when the dot size decreased from 200nm to 50nm. We interpreted this as a combined effect of quantum confinement and process related strain. A depolarisation effect due to the formation of quantum sized dots was also observed in the photoluminescence with decreasing dot size. Further work to apply bias to the coupled dots and to use photoluminescence excitation and Raman scattering is in progress.

DENSITY OF STATES EFECT IN RESONANT TUNNELING THROUGH SINGLE IMPURITY LEVELS IN SEMICONDUCTOR DOUBLE BARRIER DEVICES

I. K.Marmorkos, and F. M. Peeters

Department of Physics, University of Antwerp (UIA), B-2610 Antwerpen

Recently resonances associated with single impurity levels were observed in transport experiments through double barrier resonant tunneling devices [1,2]. This opens the possibility for transport experiments to perform spectroscopy of single atomic-like levels in semiconductor microstructures. For a correct interpretation of the experimental results a detailed theory is needed to relate the observed resonances with the position of the impurity levels and the current with the extend of the localized electronic state. We provide such a theory in the present work. Previous theoretical treatments concentrated mainly on tunneling through impurity levels in single barrier structures.

The current in this problem is no longer determined by a single overlap integral between the impurity wavefunction and the electron at the emitter. Note that if this would have been the case one should also observe resonances with excited D^0 states. We find that due to the broken translational symmetry, because of the presence of the impurity, the tunneling density of states for the ground level 1s of D^0 configuration results in a much stronger current than the one through the excited D^0 levels (i.e. $2p^-$ or $3d^{-2}$). We find that the tunneling current decreases as a function of an externally applied magnetic field, in accordance with the experiments, due mainly to the corresponding shrinkage of the D^0 wavefunction. This is equivalent to a decrease of the effective tunneling area.

The fact that excited states of D^0 cannot be observed in such devices, brings D^- as the best candidate for the explanation of a novel peak in the resonant current observed [2] at higher bias. D^- is the simplest many body system realized in a solid, and constitutes the analog of H^- in Astrophysics, where two electrons are bound to a positive center. Now two electrons are available for tunneling which results into a substantial increase of the current through this level. The impurity levels in the well are obtained through a variational calculation, after which the transfer Hamiltonian formalism was used to calculate the magnitude of the tunneling current through the ground state $|1s, 1s>$ of D^-, and compare it with the current though the D^0 ground state level. The importance of screening due to electrons in the emitter on the resonant tunneling current is also investigated.

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EXCITON QUANTUM BEATS IN TYPE II SUPERLATTICES WITH IN-PLANE MAGNETIC FIELD

I.V. Mashkov, C. Gourdon, P. Lavallard

Groupe de Physique des Solides - Universités Paris 6 et 7 - CNRS URA 17

Tour 23 - 2, place Jussieu 75005 Paris - France

The observation of quantum beats (QBs) in the photoluminescence (PL) decay of excitonic states provides valuable information on the splitting of energetically closed states and on the spin relaxation and recombination times[1].

An in-plane magnetic field couples the radiative and non-radiative states of the heavy exciton in GaAs/AlAs superlattices. QBs are detected in the case of quasi-resonant excitation of the excitonic states with linearly polarized excitation. In type II superlattices, owing two the coupling of heavy and light holes at the interfaces, the radiative exciton doublet is split into two states dipole-active along the [110] and [1$\bar{1}$0] directions, respectively. Therefore, with incident polarization along [110] ([100]) direction the difference of calculated PL intensities $I_{\parallel}$-$I_{\perp}$ (with polarization parallel and perpendicular to the incident one) is the sum of two (four) oscillating terms. Experimentally, depending on the incident polarization and the field value, one or more periods are observed and interpreted. The electron transverse g-factor and the zero-field splitting of the radiative states are obtained. We show that in this geometry QBs can also be observed on the total PL intensity because only the radiative part of the excited excitonic states is detected.

Whereas with linearly polarized excitation QBs are observed only in the case of quasi-resonant excitation, with circularly polarized excitation, exciton QBs are observed with both resonant and band-to-band excitations. In the latter case this is explained because the exciton states formed after relaxation of the excited electron-hole pairs are linear combinations of the exciton eigenstates in magnetic field. At high field, with resonant excitation two periods are observed whereas with band-to-band excitation only one period, the smallest one, is observed. By comparing these experimental results with the QB signal calculated in the density matrix formalism, we evaluate the energy and spin relaxation time of the electron-hole pairs and show that the hole has a much faster spin relaxation time than the electron.

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Interface Roughness Correlation and Narrow Exciton Lines in CdTe/CdZnTe Strained Quantum Wells

N.T. Pelekanos, N. Boudet, J. Eymery, H. Mariette*
Département de Recherche Fondamentale sur la Matière Condensée
CEA / Grenoble, 17 rue des Martyrs, 38054 Grenoble, Cedex 9, France

The exciton inhomogeneous linewidth Γ_{inh} in CdTe/CdZnTe quantum wells (QWs) as a function of QW width L, exhibits a remarkable behavior: *as L decreases, Γ_{inh} also decreases.* This is in striking contrast with previous results on other QW systems, including the GaAs/AlGaAs one, where typically decreasing L implies a strong increase of Γ_{inh}, consistent with the picture that for narrow QWs the exciton wavefunction samples more the interface region.

We measured Γ_{inh} from transmission spectra at T=2K on a series of single CdTe/$Cd_{.86}Zn_{.14}Te$ QW samples with varying QW thickness L=25-130Å, grown coherently on (100) $Cd_{.88}Zn_{.12}Te$ substrates. For L≥100Å, Γ_{inh}≈1meV (FWHM), a value which can be succesfully attributed to the standard monolayer (ML) interface model, i.e. the formation at the heterointerfaces of monolayer islands of lateral size comparable to the exciton Bohr radius [1]. For L≤100Å, however, we observe a decrease of Γ_{inh} down to, for example, 0.5meV for L=40Å. This value is to be compared to about 3meV, the estimated value for Γ_{inh} within the ML-model for the same L. To explain this unusual behavior, we are led to the notion of interface roughness correlation. In this picture, as L decreases the two "imperfect" QW heterointerfaces are increasingly correlated. In other words, for sufficiently small L the growth of the QW layer occurs in such a way that it preserves the roughness topography of the first heterointerface and results to a reduced average thickness fluctuation along the QW plane and hence to reduced Γ_{inh} values.

The existence of interface roughness correlation in our system is confirmed by synchrotron x-ray scattering measurements at large incidence angles [2]. The sample used was a 50-period 46/43Å CdTe/$Cd_{.78}Zn_{.22}Te$ superlattice (SL) grown in identical conditions as the single QW samples. The diffuse scattering intensity around the SL Bragg peaks is essentially due to interface roughness, which can be either correlated or uncorrelated. However, correlated roughness contributes to the diffuse intensity mainly at the SL Bragg planes, whereas uncorrelated one to all reciprocal space. In strong support of the interface roughness correlation model, our results clearly show for the above sample the existence of significant roughness correlation along the growth direction, as illustrated by the periodic peaks observed in the diffuse scattering intensity. Ongoing work focuses on the crucial role of strain in producing interface roughness correlation effects.

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Exact calculation of single electron inverter characteristics

S. W. Hwang and Y. S. Yu

Dept. of Electronics Engineering, Korea University
Anamdong, Sungbukku, Seoul 136-701, Korea

Recently, there have been many proposals and calculation results of single electron transistor (SET) circuits. In most analysis techniques of the circuits including many SET's, the interconnections between two SET's have been considered as relatively large electrodes. Such a large interconnection can take many electrons without much energy loss and can be approximated as a reservoir. In that case, the probabilistic electron distribution of the Coulomb island of an individual SET can be calculated independently of the others [1].

However, in realistic SET circuits with high integration capacities, the interconnection between two SET's will form another "small" Coulomb island and the approximate calculation based on independent probability distribution may be problematic.

We would like to present the exact calculation results of a typical SET inverter consisting of two SET's in series. The interconnection between two SET's has been treated as a Coulomb island and the joint probability distribution of three Coulomb islands (two islands from two SET's and one island from the interconnection) has been obtained. Our exact calculation results shows many discrepancies from the approximate calculations and we will present such discrepancies at various temperatures and values of junction capacitances. Furthermore, our results represent a full joint probability distribution in three dimensional phase space (three Coulomb islands) and we will also discuss the shape of the probability distribution function at various bias conditions.

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Fluoridation of Carbon Nanotubes Including Nanoparticles

Haruo Yokomichi, Teruo Okina, Seiji Akita* and Yoshikazu Nakayama*

Department of Electronics and Informatics, Toyama Prefectural University, Kosugi, Toyama 939-03, Japan

*Department of Electronics and Physics, Osaka Prefecture University, Sakai, Osaka 530, Japan

Much attention has been attracted to carbon nanotubes and nanoparticles since nanostructure devices, *e.g.*, low-dimensional devices can be fabricated using those materials. In order to fabricate the low-dimensional devices such as quantum wire ones, an encapsulation of the atoms into the nanotubes and then an opening of those edges should be required. Therefore we investigate the basic properties of as-grown and fluorinated carbon nanotubes including nanoparticles.

In this study the crude carbon nanotubes which include carbon nanoparticles were used and fluoridation of the sample was done with plasma CVD method using CF_4 gas. In order to investigate the basic properties of such samples, electron spin resonance (ESR), electrical conductivity and transmission electron microscope (TEM) measurements were carried out. ESR measurements were done operating at 9.1 GHz with a field modulation frequency of 100 kHz between 123K and 473K. From the ESR measurements it is found that both the crude and the fluorinated samples constituted with two components. One is temperature independent in ESR intensity and obeys Pauli law, while another is temperature dependent in that and obeys Cure law. These results show that the origins of the former and the latter are due to the conduction and the defect electron, respectively. Moreover the fluorinated sample have much temperature dependent component in comparison with the crude sample. It is suggested that opening of the edge in nanotubes can occur with fluoridation. Relation between the results of ESR and TEM images are also discussed.

Contact person: Professor Haruo Yokomichi
Complete address: 5180 Kurokawa, Kosugi-machi, Imizu-gun, Toyama 939-03, Japan
Tel: +81-766-56-7500 (ext.453), Fax: +81-766-56-8021,
e-mail: yokomiti@pu-toyama.ac.jp, Preference: poster presentation

Exciton Spin-Dynamics in $Zn_{1-x-y}Cd_xMn_ySe/ZnSe$ and $Zn_{1-x}Mn_xSe/ZnSe$ MQWs

L. M. Smith, A.R. Hodges, G. A. Balchin, and C. D. Poweleit
Department of Physics, University of Cincinnati, Cincinnati, OH 45221-0011
B. T. Jonker
Naval Research Laboratory, Washington, DC

Using polarized time-resolved magneto-photoluminescence spectroscopy we study the spin-relaxation of excitons in $Zn_{1-x-y}Cd_xMn_ySe/ZnSe$ and $Zn_{1-x}Mn_xSe/ZnSe$ multiple quantum wells. These quantum systems are grown homogeneously strained directly on GaAs substrates so that the heavy-light hole degeneracy is removed, and the heavy-hole exciton becomes the ground state. Modest magnetic fields are used to split the heavy-hole exciton into a spin-multiplet with two allowed optical transitions $|S_{hh},S_e\rangle = |+3/2,+1/2\rangle$ and $|-3/2,-1/2\rangle$ whose separation in energy is much larger than the lattice temperature, k_BT. By photoexciting electron-hole pairs equally into these spin states using a linearly-polarized ultrafast laser pulse, the excitons can be prepared in extremely non-equilibrium spin distributions. In these experiments, we study the return of these exciton spins states to thermal equilibrium with the crystal lattice.

At the earliest times after the laser pulse, the exciton spins exhibit an initial temperature of 90 K in all of these quantum wells. The subsequent relaxation of the spin system in the $Zn_{1-x}Mn_xSe$/ ZnSe system, however, depends strongly upon the Mn concentration. At low Mn-concentrations (< 2% Mn) *no relaxation* of the exciton spins is observed during the lifetime of the excitons. At higher Mn-concentrations, an initial relaxation to lower temperatures is observed with a relaxation time of 50 ps. However, this initial relaxation ceases once the exciton spin temperature reduces to a temperature which is characteristic of the Mn-concentration in each sample (e.g. 60 K for 4% Mn, 40 K for 14% Mn samples). We compare these results with measurements in ZnCdMnSe/ZnSe multiple quantum wells, where the electrons and holes are confined to the ZnCdMnSe quantum well. In every case, the exciton spins *never fully equilibrate* with the lattice.

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Model for Selective Compositional Mixing in AlGaAs/GaAs Superlattices Induced by Focused Ion Beam Implantation

R. Gass and H. E. Jackson

Department of Physics, University of Cincinnati, Cincinnati, OH, 45220-0011, USA

Compositional interdiffusion of multiple quantum well structures is widely used to tailor material properties for a variety of applications. We have modeled compositional diffusion using both a straightforward diffusion model and a modification of the model suggested by Chen and Steckl. [1] We calculate the time evolution of the compositional diffusion using both models, and are able to provide an explanation of several experimental observations, including the observation of a strong depth dependence of the compositional mixing.

Calculations will be presented for two specific multiple quantum well structures each undergoing focused ion beam implantation followed by rapid thermal annealing. The first is a $Al_{0.5}Ga_{0.5}As$/GaAs superlattice structure with equal 50nm barrier and well widths implanted with a Si^{++} energy of 220 keV at a dose of $3x10^{15}$ cm^{-2} The second is a $Al_{0.3}Ga_{0.7}As$/GaAs superlattice structure with equal 3.5 nm barrier and well widths. implanted with a Si^{++} energy of 100 keV at a dose of $1x10^{14}$ cm^{-2}. Using a model that includes an early time vacancy injection term which implies a dependence of the diffusivity on the time derivative of the vacancy concentration, we obtain good agreement with the observations by several groups of a strong depth dependence of the mixing process, that is the observation of a "pinch off" region. These calculations suggest that the modeling of compositional intermixing in multiple quantum well structures may provide guidance in the fabrication of structures utilizing compositional mixing such as quantum wires and DBR laser.

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The Effects of Interdiffusion on the Composition and Confinement Energies of AlGaAs/GaAs Single Quantum Well Structures

P. J. Hughes,[a] B. L. Weiss,[a] and H. E. Jackson[b]

[a] *Department of Electronic and Engineering, University of Surrey, Guildford, Surrey, GU2 5XH, UK*

[b] *Department of Physics, University of Cincinnati, Cincinnati, OH, 45220-0011, USA*

The behavior of the subband structure in AlGaAs/GaAs single quantum well structures due to interdiffusion across the well/barrier interfaces has been investigated for a series of different quantum well widths and a fixed Al barrier composition using a theoretical model developed by Li et al. [1]. Variations of the allowed interband transitions as a function of interdiffusion are calculated for as-grown quantum well widths of 2.5 nm, 5.0 nm, and 10.0 nm including the competing effects of both the confinement energy of the subband states and the composition of the bandgap energy in the quantum well. The understanding of these are interrelated, and are found to be strong functions of the as-grown well widths with the higher order transitions more sensitive than the ground state transitions especially during the early stages of interdiffusion. The rate of change of the interband transitions is also found to be dependent on the spatial probability distributions and effective well widths of the subband energy states, together with the effective well depth.

These results are relevant to the interpretation of experiments using vacany or impurity induced diffusion to create structures including quantum well diodes and low loss channel waveguides. More generally, experimental characterization using photoluminescence excitation and photoreflection spectroscopy, which determine not only the ground state transition energies but also the higher order transition energies explored here, can be interpreted using the present results to provide a more detailed picture of the interdiffusion process, and thus an accurate picture of the properties of engineered quantum well structures.

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Magneto-exciton localization at interface roughness in quantum wells and quantum wires

M. J. S. P.Brasil, A. L. C. Triques, M. V. Marquezini, I. F. Costa, J.A.Brum, M. A. Cotta,

Instituto de Física, UNICAMP, 13083-970 Campinas SP, Brazil

A. A. Bernussi

CPqD, TELEBRAS, 13088-061Campinas SP, Brazil

Most of the quantum-wires structures grown up to now with different techniques show some indication that interface roughness influences their optical properties, such as a broad luminescence emission and a non-negligible Stokes shift. Interface roughness gives rise to exciton localization and may hamper the evidence of exciton confinement. Nevertheless, localization effects have so far been neglected in the analyses when inferring exciton confinement from experimental data.

We investigate the interface roughness localization in an InGaAs/InP structure presenting a quantum-well-like (QW) and a quantum-wire-like (QWW) state. The QWW state is formed at an InGaAs layer grown at the steeper side of a saw-toothed-like InP surface[1]. We use magneto-optics to probe the exciton localization and confinement, varying the temperature and the angle of the external magnetic field relative to the sample. The angle dependence of the magneto shifts from the emission lines corresponding to the QW and QWW states is analyzed considering the special geometry of our structure. This analysis unambiguously demonstrates the existence of lateral confinement for the QWW state. Temperature dependent results show that interface localization plays a significant role in the measured exciton magneto-shifts, for both the QW and QWW states. As we increase the temperature, the ratio between free and interface-localized excitons increases and the magneto-shifts increase, reflecting a decrease of the interface-localization component. From the comparison between our results and calculations of the magneto-exciton in the presence of interface defects, we are able to clearly distinguish the exciton localization due to interface roughness from lateral confinement and to describe the degree of localization by effective parameters.

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Magneto-optical studies of two-dimensional electrons in asymmetric coupled double quantum wells

Joo In Lee[a], Kyu-Seok Lee[b], Hun-Kyun Na[c], Hyung Kyu Lee[d], Dongho Kim[a], Gukhyung Ihm[e]

[a]*Spectroscopy Laboratory, Korea Research Institute of Standards and Science, Taejon 305-600, Korea*
[b]*Research Department, Electronics and Telecommuniations Research Institute, Taejon 305-600, Korea*
[c]*Joint Research Facility Division, Korea Basic Science Center, Taejon 305-333, Korea*
[d]*Department of Semiconductor Science, Chungbuk National University, Cheongju 360-736, Korea*
[e]*Department of Physics, Chungnam National University, Taejon 305-764, Korea*

We investigated magneto-photoluminescence (PL) of two-dimensional electrons in GaAs/AlGaAs asymmetric coupled double quantum wells (ACDQW's) with 100 Å and 200 Å GaAs wells and 25 Å AlGaAs barrier at 1.8 K. From the Hall effect measurement, the electron density and Hall mobility were obtained to be 4.1×10^{11} cm^{-2} and 1.6×10^{5} $cm^2/V.s$, respectively. We observed in zero-field PL spectra a strong transition from the second electron subband (E2) to the first heavy-hole subband (HH1), originated from the wide well (WW), and weak transitions from E1 to HH4 and acceptor binding hole (A^o), from the narrow well (NW). The subband energies are in accord with the self-consistent subband calculation including many body effects of the Hartree's and exchange-correlation potentials. In magneto-PL spectra, as shown in Fig. 1, it is interested in having observed the Landau level transitions from E2 to HH1 as well as those from E1 to HH4. It is evident that both E1 and E2 subbands are occupied by electrons. Figure 2 shows the magnetic field dependence of the luminescence peaks for E2-HH1 and E1-HH4 transitions. In the case of E1-HH2 transition, the peak position of each Landau level changes linearly with magnetic field except for the high field region in which the Landau level begins to depopulate. This deviation was reported to arise from many body effects. [1] In NW, electron and heavy-hole effective masses obtained from the field dependence of E1-HH4 Landau level and E1-A^o peaks are $m^*_{e1} = 0.071\ m_o$ and $m^*_{hh4} = 0.148\ m_o$, respectively. The electron effective mass is consistent with the previous theoretical value. [2] On the other hand, surprisingly, the E2-HH1 transition shows nonlinear and small field dependence like excitonic behavior in low magnetic field although E2 was already occupied by electrons. This result is caused by the excitonic enhancement near Fermi level because its location is just above E2.

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TuD Chaos in nanostructures

Quantum Chaos with Interactions: Experiments in Coulomb Blockaded Quantum Dots.

C. Marcus, Stanford University

Electronic systems smaller than the electron dephasing length exhibit random but repeatable fluctuations as external parameters are varied. These and other mesoscopic effects have universal statistical properties, i.e. properties that are largely material independent. These universality aspects of mesoscopic fluctuations can be associated with a more fundamental universality of quantum systems whose classical analogs are chaotic. In the last few years, the universal aspects of mesoscopic fluctuations have been explored using a variety of theoretical tools and have been studied experimentally in a number of physical systems, in particular in ballistic quantum dots fabricated from high mobility semiconductor heterostructures.

An important recent development in this field in the past year has been an effort (both experimentally and theoretically) to include the effects of strong electron-electron interaction in the quantum interference problem underlying mesoscopic fluctuations, and to move beyond the single-particle picture of electron trajectories and electronic wave functions.

This talk will describe our recent experiments on mesoscopic conductance fluctuations in ballistic GaAs/AlGaAs quantum dots in the regime of Coulomb blockade. At temperatures below the single particle level spacing, Coulomb Blockade conductance peaks fluctuate in amplitude (and even vanish) due to variation in the coupling of the wave function in the dot to the leads. The measured statistics of these fluctuations are in excellent agreement with a random matrix theory of single-particle wave functions in the dot at both zero and nonzero magnetic field. Between peaks, the strongly blockaded valleys also show mesoscopic fluctuations. For this regime, the theory of elastic cotunneling has recently been extended by Aleiner and Glazman to include fluctuations. Again, good agreement is found with experiment.

Finally, we will discuss Coulomb blockade peak fluctuations as a continuous function of magnetic field. The field scale of the fluctuations is on the order of 1 flux quantum through the quantum dot, which is larger than the value expected from simple semiclassical arguments.

Scaled Field Studies of Quantum Chaotic States in Wide Potential Wells

P.B. Wilkinson, A. Thornton, T.M. Fromhold, T.J. Foster,
L. Eaves, F.W. Sheard, P.C. Main and M. Henini

Department of Physics, University of Nottingham, Nottingham NG7 2RD, UK

The current-voltage characteristics $I(V)$ of resonant tunnelling diodes (RTDs) with a wide ($\sim$ 100 nm) quantum well (QW) in a high tilted magnetic field $B \sim 10$ T reveal complex series of quasi-periodic resonant peaks [1-3]. The tilted magnetic field produces chaotic classical motion in the QW. Although most orbits are highly irregular, a variety of unstable but periodic orbits also exist. Each periodic orbit generates regular fluctuations in the density of quantised energy levels, and also wavefunction 'scarring', a concentration of probability density along the orbital path [4-5]. Both of these effects generate quasi-periodic resonant peaks in $I(V)$. When a particular periodic orbit exists over a wide range of bias voltages, many associated resonant peaks are observed in $I(V)$. The corresponding periodic classical orbit can then be identified from the voltage spacings of the resonant peaks. By contrast, if the periodic orbit only exists for a small range of bias voltages, the observed resonant structure changes rapidly with V. It is then extremely difficult to relate particular resonant peaks to the underlying classical orbits.

Here we investigate magnetotunnelling curves $I(B)$ obtained by varying *both* the magnetic field and the applied bias voltage so as to keep $m^*(V)V/B^2$ constant, where the effective mass $m^*(V)$ includes the effects of conduction band nonparabolicity. We show that this novel scaled field measurement technique ensures that the classical phase space accessible to the tunnelling electrons is *identical* for all fields. Electrons in the QW therefore always execute the same periodic orbits. Each closed orbit produces many truly periodic resonant peaks in $I(B)$ with a period $\Delta B = h/S$ where S is the classical action. Fourier analysis of the magnetotunnelling data is used to distinguish different series of oscillations and accurately determine the classical actions of the associated classical orbits. This enables us to identify distinct classical orbits corresponding to many different series of resonant peaks. In previous magnetotunnelling studies undertaken at fixed B [2], the origin of some of these resonant peaks was unclear because the classical phase space was extremely sensitive to small changes in the applied bias voltage. Quantum-mechanical calculations of $I(B)$ are found to be in excellent quantitative agreement with the experimental data. These calculations enable us to relate the observed resonant peaks directly to individual eigenstates in the QW which are strongly scarred by particular unstable periodic classical orbits.

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Transition between Synchronization and Spatio-Temporal Chaos in Doped GaAs/AlAs Superlattices

Yaohui Zhang[1], *Robert Klann*[1], *Holger T. Grahn*[1,2], *and Klaus H. Ploog*[1]

[1]*Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, D-10117 Berlin, Germany*

[2]*Research Center for Quantum Effect Electronics, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152, Japan*

The nonlinear dynamics induced by resonant tunneling between quantum wells can result in self-oscillations of the current in weakly coupled superlattices (SLs). Frequencies from the MHz regime up to several GHz have recently been reported in weakly to moderately doped GaAs/AlAs SLs.[1,2] The oscillations originate from electric-field domain formation with an oscillating domain boundary. Currently, arrays of non-linear oscillators and spatio-temporal chaos are both very important topics, which are extensively investigated. Since dynamical systems with a small number of degrees of freedom are rather well understood, the research interest has moved to spatially-distributed nonlinear dynamical systems, in particular to arrays of coupled oscillators. However, most studies have been theoretical investigations, while only very few reports deal with experimental studies.

We have experimentally observed the transition between periodic and chaotic current oscillations in weakly-coupled GaAs/AlAs SL by simply changing the applied bias, i.e., without any driving voltage. The SL consists of 40 periods of 9.0 nm GaAs wells and 4.0 nm AlAs barriers. The GaAs wells are Si-doped with a density of 3×10^{17} cm^{-3}. Periodic current oscillations are observed for voltage regions with positive differential conductance in the time-averaged I-V characteristic. However, in negative differential conductance regions of the I-V characteristic chaotic windows appear, while quasi-periodic modes are completely absent. The transition from chaotic to periodic behavior occurs over a very small voltage range on the order of mV, while the transition from synchronized to chaotic oscillations takes place through a random-enhancing process. For a biased, weakly coupled SL, sequential resonant tunneling between adjacent quantum wells leads to a complete loss of the phase memory of the electrons after a full sequential tunneling process. For each quantum well there are two dynamical variables, the electron density and the electric field. So, a weakly coupled SL can represent a spatially distributed, non-linear dynamical system with many degrees of freedom. In such a system, the coupling between the degrees of freedom is repulsive in the chaotic windows, while in the periodic windows it is attractive.

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TuP Poster session

Hopping Transport in Superlattices

S. Rott, N. Linder, and G.H. Döhler

Institut für Technische Physik 1, Universität Erlangen, Erwin-Rommel-Str. 1, D-91058 Erlangen, Germany

The transport properties of semiconductor superlattices have found considerable interest because negative differential conductivity (NDC) can be obtained at relatively low electric fields. This phenomenon is usually described within a semiclassical picture such as the Esaki-Tsu model or theories based on the Boltzmann equation. These models, however, cannot account for the discrete nature of the eigenstates of the Wannier-Stark ladder which becomes important when the Bloch frequency exceeds the mean carrier scattering rate. In this limit transport processes are governed by hopping transitions between the partially localized Wannier-Stark states rather than scattering between delocalized Bloch states. For the case of strongly coupled superlattices this situation can be obtained if the spacing of the Wannier-Stark ladder eFd is still well below the miniband width Δ.

We calculate the dc-current in this regime from the transition rates between the Wannier-Stark states. In our numerical model we start from the exact wavefunctions of the superlattice and include both impurity and phonon scattering. We then obtain the electron drift velocity by considering the thermal in-plane distribution function of the Wannier-Stark levels and by summing over all possible hopping processes.

Our results deviate significantly from those of the Esaki-Tsu model. The numerical calculations can be interpreted using the results of analytical expressions for the high-field limit. We can identify two different regimes of field dependence of the drift velocity, obeying power laws F^{-n}. For "moderate" fields n is large, resulting from increasing field dependent localisation of the wavefunctions. For higher fields, however, the wavefunctions become equivalent to the Wannier functions of the superlattice and the localization saturates. Therefore, a lower exponent n is obtained. The critical field for the transition between these regimes depends on the amount of coupling between adjacent superlattice periods, i.e., the delocalisation of the Wannier functions.

Anderson and Stark Localization in GaAs/(AlGa)As Disordered Superlattices

[1]G.F. Lorusso, [2]V. Capozzi, [3]F. Tassone, [1]J.L. Staehli, and [4]D Martin

[1]Institut de Physique Appliquée, Ecole Polytechnique Fédérale,
PH-Ecublens, CH-1015 Lausanne, Switzerland;
[2]Dipartimento di Fisica dell' Università di Bari,
Via Amendola 173, I-70126 Bari, Italy;
[3]Institut de Physique Theorique, Ecole Polytechnique Fédérale,
PH-Ecublens, CH-1015 Lausanne, Switzerland;
[4]Institut de Micro- et Optoélectronique, Ecole Polytechnique Fédérale,
PH-Ecublens, CH-1015 Lausanne, Switzerland.

Optical measurements on disordered GaAs/(AlGa)As superlattices are reported. The results are compared with numerical calculations obtained by means of the transfer matrix method [1]. In particular, full optical evidence of weak localization and of a disordered-induced fine structure in this localization limit is reported. The equivalence between such a disorder-induced (by Anderson localization) fine structure and the electric-field-induced (Stark ladder) fine structure is then shown. Furthermore, the photoluminescence intensity of disordered superlattices shows a weaker decrease with temperature with respect to the ordered case, in good agreement with recent numerical results [2], thus suggesting technological applications of random superstructures in light emitting devices.

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Field induced interlayer interband coupled states in aperiodic InAs/GaSb heterostructures

Gyungock Kim

Research Department, Electronics and Telecommunications Research Institute

Yusung P. O. Box 106, Taejon, Korea 305-600.

The effects of the external bias and the interfacial composition on the aperiodic InAs/GaSb heterostructure have been investigated using the scattering theoretic Green's function technique incorporated with the realistic bandstructures for constituent materials of the heterostructure. The formalism can include the band nonparabolicity, multiorbital effect, aperiodicity, and the high electric field effect in layered-structures, and directly handle the interface matching condition and interlayer multisubband interaction.[1] The calculated local density of states of a heterostructure along the growing direction of the heterostructure, under application of an electric field perpendicular to the layers, shows formation of interlayer interband coupled states between the light-hole-like quasibound valence state and the quasibound electron-like conduction state. The nonequilibrium Green's function calculation[2] of electron tunneling current shows that the interlayer interband coupled subbands between adjacent layers enhance the peak current density by facilitating electron resonant tunneling, and can be utilized in the electron transport. The calculated spectral local density of states of a heterostructure also shows that the GaAs-like interface shifts the energies of light-hole-like and electron-like quasibound states to lower energy side than those of the InSb-like interface case, which agree with experimental results.

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CARBON-BASED SUPERLATTICES OF NEW TYPE

A. Baranov, [1]P. Kondrashov, [1]I. Smirnov, and [2]S. Tereshin

Research Institute of Vacuum Technique, 7 Nagorny Proezd, Moscow 113105, Russia.
[1]Moscow State Institute of Electronics and Mathematics. Bol. Vuzovsky per. 3/12, Moscow 109028, Russia
[2]Institute of Radio Engineering and Electronics of the Russian Academy of Science, 11 Mokhovaya str., Moscow 103907, Russia.

A large number of crystalline and amorphous superlattices based on a combination of layers of different materials have now been investigated. In such lattices, potential barriers and wells are formed by a potential jump at the interface, which is due to a difference in chemical nature of the materials involved.

In this paper, we consider the possibility of creating a new class of superlattices on the basis of only one type of material, namely carbon. The underlying principle is based on the ability of carbon atoms to have several types of chemical bond hybridization, such as sp^1, sp^2, and sp^3; these types are associated with materials having different physical properties (e.g., carbine, graphite, and diamond). We analyse how the variation range of the properties of thin layers composed of carbon atoms depends on the percentage of carbon atoms with different types of bond hybridization.

It is shown that by using ion-plasma deposition methods, one can form superthin carbon layers with widely differing properties: optical band gap in the range from 0.4 eV to 3.2 eV, resistivity (no doping) from 1 to 10^8 Ohm*cm, refractive index from 1.7 to 2.4, density from 1.4 to 2.4 g/cm^3.

The technique for creating carbon-based superlattices with period up to 24 Å and the period number from 10 to 150 was developed using on-line deposition layer control. It is shown by the X-ray diffraction method and the secondary ion mass spectroscopy that the structures obtained have high periodicity and a good interface. The volt-ampere characteristics of the superlattices obtained were studied. The charge-carrier transfer and scatter mechanisms are discussed.

INTERLAYER SPIN COHERENCE IN ANTIFERROMAGNETIC EuTe/PbTe SUPERLATTICES OBSERVED BY POLARIZED NEUTRON DIFFRACTION

V. Nunez†, G. Springholz⋆, T. M. Giebultowicz§, H. Kępa§, K. I. Goldman§, C. F. Majkrzak†, and G. Bauer⋆

† - *National Institut of Standards & Technology (NIST), Gaithersburg, MD 20899, USA;*
⋆ - *Institut für Halbleiterphysik, Johannes Kepler Universität Linz, A-4040 Linz, Austria;*
§ - *Department of Physics, Oregon State University, Corvallis, OR 97331, USA.*

PbTe is a non-magnetic semiconductor, and EuTe, also a semiconducting compound, is a Type II FCC antiferromagnet below $T_N = 10$ K. As shown by high-resolution X-ray diffraction, (111) binary superlattices grown from these materials are of remarkably good crystalline quality. Our earlier neutron diffraction studies of $[(EuTe)_m|(PbTe)_{3m}]_N$ samples (with m=2-7, N=200-600) using unpolarized beams showed that the Type II AFM ordering is preserved in the EuTe layers [1]. However, the lattice strain always selects an arrangement in which (111) ferromagnetic spin sheets (characteristic for the Type II structure) are *parallel* to the layers. In addition, in samples with $n \leq 5$ scans through the AFM reflections reveal pronounced patterns of satellite peaks — a clear signature of a coherence in the spin ordering in consecutive EuTe layers. This effect indicates that Eu-Eu exchange interactions are transfered through non-magnetic PbTe barriers even as thick as 55Å! The origin of this surprisingly long-range interaction can not be understood on the grounds of the existing theories of interlayer magnetic coupling: in all of those models high concentrations of *conduction electrons* play a crucial role [2], whereas EuTe is insulating at low temperatures, and in PbTe n is as low as $\sim 10^{17}\text{cm}^{-3}$. In order to obtain additional experimental insight in the system that might shed more light on this problem, we have begun new investigations of the system behavior in external magnetic fields using *polarized* neutron diffraction. This technique offers information about the Eu spin orientation in the (111) growth plane, not obtainable by the conventional method — i.e., it is particularly useful for studying the AFM domain arrangement in the EuTe layers. While the (111) symmetry allows six non-equivalent Type II configurations, gradually increasing external field should align spins in all domains perpendicular to H and, at the same time, it should interfere with the interlayer coupling forces. Eventually, this process is expected to destroy the interlayer spin coherence — detailed "monitoring" of the process may therefore reveal the much needed information about the *interlayer coupling strength.* Our experiments show that there are drastic differences in the system behavior depending on the "cooling history". If the sample is cooled at H=0, then a modest field (~0.5 T) indeed leads to the expected domain rotation. Further H increase induces a growing *ferromagnetic component*, and gradually supresses the AFM one — however, the interlayer coherence in the AFM ordering can be still seen up to surprisingly high H values (~5 T). On the other hand, if the sample is cooled through T_N with the field on, then H<0.5 T already destroys the interlayer correlations. Explanation of the observed facts and estimates of the interaction strength based on model calculations will be presented, and some possible physical mechanisms underlying the interlayer coherence will be discussed.

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In-Plane Optical Anisotropy of (N11) GaAs/GaAlAs Superlattices

Z. Yang, Yongning Sheng, and Y. Q. Wang
Department of Physics, Hong Kong University of Science and Technology, Clearwater Bay, Kowloon, Hong Kong.
Fax: 852-2358-1652, e-mail: PHYANG@USTHK.UST.HK

The optical anisotropy of (311) and (511) GaAs/$Ga_{0.7}Al_{0.3}As$ SL's, and for comparison (111) GaAs/$Ga_{0.7}Al_{0.3}As$ SL's, with well/barrier thickness of 50/50 Å , 35/35 Å, and 25/25 Å is studied. Reflectance difference spectroscopy (RDS) is employed, since RDS is only sensitive to in-plane optical anisotropy and is therefore ideal for such study. An unique setup of RDS and Fourier Transform Spectrometer (FTS) is employed in the spectral range near the bandgap of GaAs, and conventional RDS is employed for higher photon energies. The SL's were grown by molecular beam expitaxy under the growth conditions that are known to avoid corrugating structures. Three series of resonances are observed in the RD spectra of (311) and (511) SL's while none is observed in the (111) SL's. The first series of two resonances near 1.5 eV are due to the optical transitions from the first confined Γ_8 heavy hole and the light hole subbands to the first Γ_6 conduction subband. The second series of one resonance near 1.8 eV is due to the transition from the Γ_7 hole subband to the first Γ_6 conduction subband. The third series of resonances near 3 eV are due to the confined states associated with the Λ and the $\Lambda + \Delta_0$ bulk states, the anisotropy of which is revealed by this work for the first time. Both positive and negative resonances are observed for the (311) and (511) SL's. The fact that resonances of both signs are observed excludes the possibility that the resonances are due to the quantum wire type structure in corrugated SL's, as in such case all resonances should have the same sign. The resonances shift to higher energy for SL's with shorter periods, a further indication that they are indeed due to the confined subbands in the quantum wells. Theoretical results using the **k*p** model will be reported along with the detailed experimental data.

Atomic Layer Epitaxy of II-VI semiconductor heterostructures

J.M.Hartmann, H.Mariette, F.Kany, M.Charleux, J.L.Rouvière and H.Ulmer-Tuffigo

Equipe mixte CNRS-CEA "Microstructures de semiconducteurs II-VI" (DRFMC/SP2M/PSC)

CEA-Grenoble 17, Avenue des Martyrs 38054 GRENOBLE Cedex 9 FRANCE

Atomic Layer Epitaxy (ALE), wich consists in sending alternately the cations (Cd, Mn, Mg) and the anions (Te) coming from elemental sources onto the substrate surface, is investigated for CdTe, MnTe and MgTe. Various methods are used to optimize the ALE growth process and to determine precisely the growth rate per ALE cycle for the different materials.

For CdTe, a 0.5 monolayer / ALE cycle self-regulated growth rate is obtained in a substrate temperature range between 260°C and 290°C. Such a growth mode has been evidenced by monitoring the Reflection High Energy Electron Diffraction (RHEED) sublimation intensity oscillations of an ALE grown CdTe layer deposited onto a MgTe buffer layer. The growth sequence leading to the deposition of one complete CdTe monolayer is thus made of two ALE cycles : the first one corresponds to the formation of a rough surface with islands covering half of the surface, whereas the second one completes the monolayer and allows recovery of the flat surface.

RHHED studies on MnTe atomic deposition, together with X-Ray Diffraction (XRD) and Transmission Electron Microscopy on ALE grown CdTe / MnTe superlattices reveal that all incident Mn atoms are incorporated during the MnTe ALE cycle, so that no autoregulated growth can be achieved. So, less than one or just one monolayer of Mn must be sent onto the surface per ALE cycle to obtain well controlled superlattices with abrupt interfaces.

As far as MgTe is concerned, an autoregulated growth at 0.7 ± 0.1 monolayer / ALE cycle can be achieved in a substrate temperature range between 260°C and 300°C. This value has been obtained by combining XRD and PhotoLuminescence (PL) data on various ALE grown CdTe / MgTe superlattices; whereas XRD gives a precise value of the superlattice period, PL is very sensitive to the CdTe thickness, allowing a precise determination of the MgTe deposited thicknesses. A new value of the cubic MgTe lattice parameter $a_{MgTe} = 6.42$ Å is thus derived.

The knowledge of the ALE growth proccess for CdTe, MnTe and MgTe allows a precise control of fractionnal monolayer deposition and opens the road to the realization of quantum wires made from tilted or serpentine superlattices grown on vicinal surfaces.

PHOTOLUMINESCENCE INTERNAL QUANTUM YIELD IN SUPERLATTICES

D. Martins, C. Gourdon, P. Lavallard

Groupe de Physique des Solides - Universités Paris 6 et 7 - CNRS URA 17

Tour 23 - 2, Place Jussieu - 75005 Paris - France

R. Planel

Laboratoire de Microstructures et Microélectronique - CNRS URP 20

196, avenue Henri Ravera 92220 Bagneux - France

We report on the intensity and temperature dependence of the internal quantum yield of photoluminescence (PL) of GaAs/AlAs superlattices (SL). The internal quantum yield is obtained by a novel method which does not necessitate the measurement of the external quantum yield[1].

A SL is grown on top of a thick GaAs layer. We make use of the GaAs PL excitation spectrum (PLE) to obtain the SL quantum yield. A step-like behavior is observed in the PLE spectrum of GaAs when the excitation energy is scanned through the SL lowest excitonic transition. Below the SL transition, the GaAs PL is directly excited by the incoming light. Above the SL transition there are two channels of excitation: the GaAs PL is directly excited by light which has not been absorbed in the SL and indirectly excited by the 97% of the SL PL light which does not escape from the sample owing to the high refractive index.

From the GaAs PLE and the SL PLE we obtain the SL quantum yield and absorption coefficient at the SL excitonic transition energy. The GaAs quantum yield is also obtained. We show that the SL quantum yield at 10K increases from 43% at an excitation density I_0=3.7 mW.cm^{-2} to 79% at $10^5 I_0$. Reabsorption effects and photon recycling processes which are certainly important when the quantum yield is large will be discussed. Despite of the increase of quantum yield, almost no change is observed on the PL decay with increasing excitation density. This is a clear indication that the PL decay is related not to the localized exciton lifetime but to the relaxation time from the free exciton or electron-hole pair states to localized exciton states. A similar behavior is observed with increasing temperature. The quantum yield decreases but the PL decay time increases.

We emphasize that the simple method described here to obtain the internal quantum yield is readily applicable to any material grown on top of another material of smaller band gap.

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Photoreflectance Measurements in GaAs-AlGaAs Asymmetric Quantum Wells

M.A.G.Soler, P.C. Morais and J. Depeyrot, Universidade de Brasília - Brasília(DF) - Brasil

J.A.N.T Soares, LNMS - IFUSP, Universidade de São Paulo - São Paulo - Brasil

G.Weimann and G.Trankle, Walter Schottky Institut, Tecnische Universitat Munchen, Germany

Single asymmetric quantum wells (SAQW's) have received a great deal of interest in recent years due to their technological applications and as a valuable system to study fundamental properties of a two dimensional (2D) electron gas. In such structure carriers are released from intentionally doped impurities in the wider gap layer diffusing into the narrower gap layer, where 2D-gas is builted. The spacer - an undoped wide gap layer - is grown in between the quantum well and the impurity sites thus offering a barrier through which carriers have to tunnel in their pathway towards the asymmetric quantum well. Optical control of the 2D-electron gas density in Si-doped GaAs-AlGaAs SAQW's has been reported by several authors. According to the authors, under strong illumination the 2D-electron gas density is washed out from the quantum well. On the other hand, the 2D-electron gas reaches its maximum value under dark conditions. In between these two limiting conditions the 2D-electron gas density may be controlled by the optical excitation intensity. A blue shift in photoluminescence measurements under strong illumination has been reported as a signature of the optical control of the 2D-electron gas in SAQW's. In this work, photomodulated reflection measurements, performed at 77K and 300K, have been used to investigate the optical control of the 2D-electron gas density in SAQW's of GaAs-AlGaAs:Si, grown by MBE. Our attention is focused on changes of the band profile at the barrier region which goes from a flat condition under strong excitation, to a triangular potential barrier under dark condition. Changes of the band profile in between these two limiting cases, were studied as a function of the pump beam intensity. For the first time photomodulated reflection spectroscopy is used to study the optical control of 2D-gas density in SAQW's.

EXCITONIC MOLECULES IN TYPE-II SUPERLATTICES

Takuma Tsuchiya,[A] Shin'ichi Katayama,[A] and Tsuneya Ando[B]

[A] *Japan Advanced Institute of Science and Technology (JAIST)*
1-1 Asahidai, Tatsunokuchi 923-12, Japan

[B] *Institute for Solid State Physics, University of Tokyo*
Roppongi, Minato-ku, Tokyo 106, Japan

Very recently, excitonic molecules in $(GaAs)_{12}/(AlAs)_{12}$ type-II superlattices have been observed in a photo-luminescence experiment. [1] The observed binding energy of 3 meV seems much larger than that in type-I superlattices. Further, it is not clear which gives the largest binding energy among some possible relative positions of two electrons and two holes in the direction perpendicular to the interfaces. This problem is peculiar to type-II superlattices, because electrons and holes are in different layers. In this study, we have performed variational calculations on the excitonic molecules in type-II superlattices and have clarified which structure gives the largest binding energy.

We consider three types of spatial structures, which are expected to give large binding energy: A) two holes in a GaAs layer and two electrons are in adjacent AlAs layers separately, A') two electrons are in a AlAs layer and two holes are in adjacent GaAs layers, and B) two electrons and two holes are in consecutive two GaAs and two AlAs layers. In classical estimation, in which electrons and holes are assumed to be point charges and to move the center of the layers, the type-B gives the largest binding energy. In quantum calculations, we have employed the Gauss-type wave function in the direction perpendicular to the interfaces for each electrons and holes and have performed variational calculations with six parameters for the type-A and A' and that with seven parameters for the type-B. Contrary to the classical estimation, it has been found that the type-A gives the largest binding energy of 2.3 meV. This difference between classical and quantum calculations comes from the broadening of wave functions in the direction parallel to the interfaces in quantum mechanics. We have also calculated the binding energy in type-I superlattices, using similar variational wave function. The binding energy is almost the same with that in type-II superlattices. Thus the binding energy is not enhanced much in type-II superlattices.

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Anomalies in the Exciton Photoluminescence Polarization of Short-Period Superlattices with Corrugated Interfaces

V.G. Litovchenko, D.V. Korbutyak, S.G. Krylyuk, and Yu.V. Kryuchenko
Institute of Semiconductor Physics, National Academy of Sciences of Ukraine,
Prospekt Nauki 45, 252650 Kiev 28, Ukraine

H.T. Grahn and K.H. Ploog*
Paul-Drude-Institut für Festkörperelektronik,
Hausvogteiplatz 5-7, D-10117 Berlin, Germany

The polarization properties of the exciton photoluminescence (PL) of short-period GaAs-AlAs superlattices exhibit an anomalous dependence on the detection angle.[1] A possible explanation connects the polarization of the exciton PL with the corrugation of the interfaces. In order to obtain a full understanding of this phenomenon, we have performed a systematic investigation of the linear polarization factor P, which is defined as the ratio of the difference to the sum of the PL intensities polarized perpendicular and parallel to the SL layer plane. The polarization factor P is measured at different detection angles Θ as well as at different rotation angles Φ. Model calculation to study the influence of different types of corrugation on $P(\Theta)$ are also performed.

Type-I and type-II GaAs-AlAs superlattices (SL) with different interface corrugations have been investigated. In type-II SLs, $P(0)$ is remarkbly larger than in type-I SLs. The SLs with well widths between 5.0 and 8.0 nm exhibit the largest polarization factor. Furthermore, $P(\Theta)$ increases by a factor of 2 to 3, when the detection angle is increased from 0 to 45°, which is in qualitative agreement with the results of the model calculations. The actual shape and the homogeneity of the corrugations can be estimated from the average value of $P(\Theta)$ and the actual dependence on Θ. Since the effect should be observable only if the lateral dimensions of the corrugation is comparable to the exciton radius (about 10 nm), these experimental results demonstrate a vertical height of the roughness of less than one monolayer. In medium size SLs, P also depends on the energetic position within the PL line, which is qualitatively explained by the stronger influence of light-hole transitions on the high-energy side of the spectrum. In ultra-short period SLs, the PL line originates from bound excitons. In this case an anomalous angular dependence is observed, i.e., the polarization factor decreases with increasing angle. The value of P is determined by the orientation of the local polarization of bound excitons, which are localized by surface defects. A theoretical modelling has to include the surface defects with a local reconstruction of the chemical hybrids.

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*on leave at: Research Center for Quantum Effect Electronics, Tokyo Institute of Technology, 2-12-1 O-okayma, Meguro-ku, Tokyo 152, Japan.

INTERWELL EXCITONS IN GaAs SUPERLATTICES

D. Birkedal, K. El Sayed, G. Sanders, C. Spiegelberg, V.G. Lyssenko, C. Stanton, and J.M. Hvam.

Mikroelektronik Centret, The Technical Univeristy of Denmark

DK-2800 Lyngby, Denmark

V.B. Timofeev

Institute of Solid State Physics, Russian Academy of Sciences

142432 Chernogolovka, Moscow district, Russia

M. Bayer

Technische Physik, Universität Würzburg

Am Hubland, D-97074 Würzburg, Germany

The formation of spatially indirect excitons in superlattices with narrow minibands is theoretically and experimentally investigated. We identify the experimental conditions for the observation of interwell excitons and find a distinct excitonic state energetically located between the 1s exciton and the onset of the miniband absorption. The interwell exciton is similar to the first Wannier-Stark localized exciton of an electrically biased superlattice. However, in the present case the localization is mediated by the Coulomb interaction of the electron and the hole without external fields.

In this presentation, we demonstrate theoretically and experimentally that interwell excitons also can form in superlattices without externally breaking the inversion symmetry. For superlattices with narrow minibands the Coulomb interaction of electrons and holes in adjacent wells is sufficient to localize the superlattice state and form interwellexcitons. The interwell exciton is observed directly in photoluminescence and absorption experiments. We confirm the 1s in-plane character of the interwell exciton by recording its diamagnetic shift in photoluminescence excitation spectra for varying magnetic fields in the growth direction.

COMBINED EXCITON - ELECTRON EXCITATION IN QUANTUM WELLS WITH ELECTRON GAS OF LOW DENSITY

V.P.Kochereshko[1], D.R.Yakovlev[1,2], R.A.Suris[1], W.Ossau[2], A.Waag[2], G.Landwehr[2]
[1]*A.F.Ioffe Physico-Technical Institute RAS, 194021 St.Petersburg, Russia*
[2]*Physikalisches Institut der Universität Würzburg, D-97074 Würzburg, Germany*

P.M.C.Christianen and J.C.Maan
High Field Magnet Laboratory, University of Nijmegen, NL-6525 ED Nijmegen, The Netherlands

A new type of elementary exitations was found in semiconductor quantum wells with low concentration of free electrons in the presence of external magnetic fields. Experimental and theoretical studies provided show that it is a combined exciton - electron excitation.

CdTe/$Cd_{0.75}Mg_{0.25}Te$ heterostructure grown by molecular-beam epitaxy on (100)-oriented $Cd_{0.96}Zn_{0.04}Te$ substrate was used for the studies. It consists of a 75-Å-thick single quantum well (QW) sandwiched by 1000-Å-thick superlattices (SLs) (30 Å/30 Å). 200-Å-thick barrier layers separate the QW from the SLs. Different tunneling probabilities for electrons and holes from the SLs into the QW, allow to control optically concentration of free electrons in the QW.

Photoluminescence (PL), PL excitation and reflectivity spectra were studied in magnetic fields up to 20 T. PL spectrum of the QW consists of two lines corresponding to a recombination of excitons localized on well-width fluctuations and to a negatively charged exciton complex (X^-) [1]. A new line (LL-line) was found in the PL excitation and reflectivity spectra in the presence of magnetic fields. An intensity of the LL-line increases strongly with the increase of electron concentration in the QW. The LL-line shows linear shift in magnetic field with a slope of about the electron cyclotron frequency. An extrapolation of the LL-line position to zero field meet the energy of 1s heavy-hole exciton (e1-hh1). A Zeeman splitting of the LL-line is equal to a Zeeman splitting of the free 1s heavy-hole excitons.

These experimental findings allow us to conclude that the LL line is determined by a combined exciton - cyclotron resonance: an incident photon creates an exciton in the ground state and simultaneously excites an electron from the first to the second Landau levels. A theoretical model of such process is developed and explains all experimental features observed. The observed resonance can be also considered in terms of excited state of the X^--comlex in strong magnetic fields.

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MAGNETOEXCITONIC OSCILLATIONS OF GROUND AND EXCITED STATES IN ASYMMETRIC QUANTUM WELL STRUCTURES

A. R. Alves
DPF, Universidade Federal de Viçosa, 36570-000, Viçosa, MG, Brazil

L. A. Cury, P. S. S. Guimarães and M. V. B. Moreira
Dept. Física, ICEX, UFMG, CP 702, 30161-970, Belo Horizonte, MG, Brazil

The Shubnikov-de Haas (SdH) effect is widely used for characterization of semiconductors. Recently, SdH-like oscillations have been seen in photoluminescence (PL) measurements. These *optical SdH* oscillations (OSdH) appear in the intensity of the PL line arising from the recombination of electrons in the second subband (e_2) of an asymmetric quantum well in which e_2 is near the Fermi energy (E_F) of the system. As the magnetic field (B) is increased, the intensity of the PL line displays maxima which are periodic in 1/B as in the *electrical SdH* effect. There are several models proposed in the literature to explain the phenomenon[1-3]. Very pronounced oscillations are also seen in the PL line arising from the recombination of electrons in the *first* subband (e_1). Up to date, no clear results have been obtained which relate the oscillations in e_1 with those in e_2.. We report here on an investigation of the OSdH in a n-AlGaAs/InGaAs/GaAs structure in which e_2 is 5 meV above E_F. We establish a clear relation between the oscillations in e_1 and e_2. The maxima in e_1 occur when a Landau level of the first subband crosses E_F , i.e., the oscillations in e_1 are in phase with those in the electrical SdH. The oscillations in e_2 are 180° out of phase with the oscillations in e_1. This shows that the processes responsible for the oscillations in the two PL lines are competitive. We show that the OSdH are due to an enhancement of the interaction between the holes in the valence band and the electrons in the first electronic subband when a Landau level of this subband crosses E_F. An increase in the intensity of e_1 will necessarily lead to a decrease in the intensity of e_2 (and vice-versa) since the intensity of both PL lines is determined by the relatively low number of photoexcited holes in the valence band.

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Photoluminescence Excitation Spectroscopy on Excitonic States of Narrow GaAs-AlGaAs Single Quantum Wells in High Magnetic Field

H.S. Ko, Y.M. Kim, W.S. Kim, D.H. Kim, Y.S. Kim, T. Schmiedel* and J.C. Woo,
Department of Physics, Seoul National University, Seoul 151-742, Korea
(T) +82-2-880-6597, (F) +82-2-871-7507, (e) jcwoo@power1.snu.ac.kr
* National High Magnetic Field Laboratory, 1800 E. Paul Dirac Dr., Tallahassee, FL 32310

Dimensionality related to the electronic confinement in low dimensional semiconductor structures has attracted attention in recent years, and a study on magnetic field (B) dependence provides direct means on this. In this work, the B-dependent electronic (or excitonic) states in very narrow GaAs-$Al_{0.25}Ga_{0.75}As$ single quantum well (SQW) are studied by both photoluminescence (PL) and PL excitation spectroscopy (PLE) at LHe temperature. The samples have very flat heterointerface and undoped high mobility GaAs layer. The field up to 20 T is applied vertically to the QW plane.

The ground (1s) and the first excited (2s) states of heavy hole coupled excitons (hh), 1s of light hole coupled exciton (lh) and 1-LO Stokes of 1s hh (LO) have been observed in 11 monolayer (ML) (28Å) SQW (See Fig. 1) and similar ones in 17 ML (47Å). The results show that the blue shifts induced by the field ($\Delta E_B = E_B - E_0$, where E_B and E_0 are the corresponding PLE positions in B and zero field) is smaller in 11 ML than in 17 ML for all the levels. In a given sample, the trend of the shifts by the field is almost the same for hh related peaks, i.e. 1s and 2s hh and LO, which contradict with previous reports. (See Fig. 2) Also observed is the fine splitting of 1s hh and even 2s hh PLE peaks for B ≥ 15T.

The preliminary results can be well explained with the low-dimensional confinement of excitons. However, after careful quadratic fits of ΔE_B with respect to B, it seems that the shift in high field still reflects the excitonic behavior for all states, even for the excited and LO-coupled states, and that the reduced mass interpretation may not be sufficient to explain the trend. The fine splittings show similar B-dependence with those related to spin-split Landau level [1] except the temperature being high (4.2K vs 2K).

The some of discrepancy observed in this experiment will be interpreted with the electron-hole pair under low-dimensional confinement.

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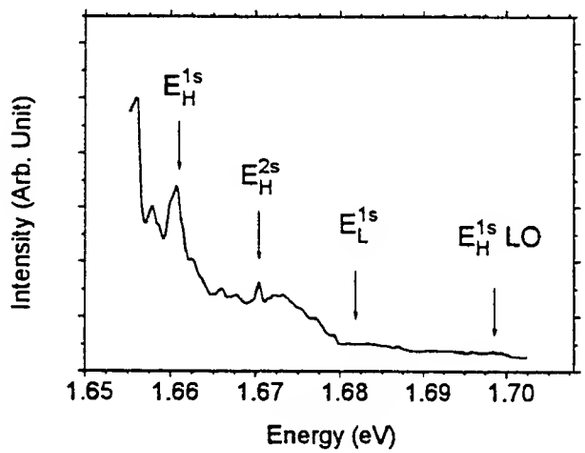

Fig. 1 : Typical PLE spectra of 11 ML SQW at B = 20 T

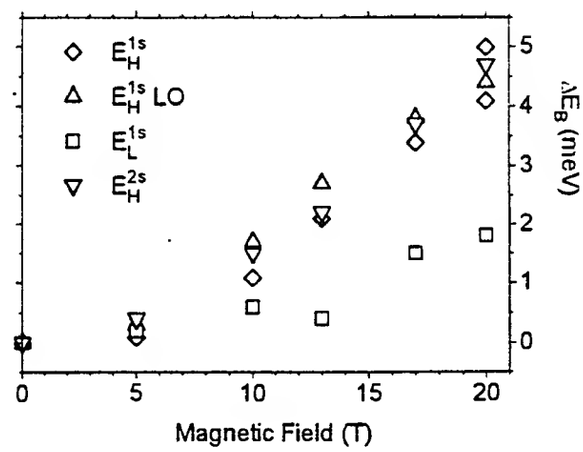

Fig. 2 : The shift of PLE positions (ΔE_B) versus magnetic field

Rapid radiative decay of excitons in $GaAs/Al_{0.3}Ga_{0.7}As$ QWs with extremely flat interfaces grown on a (411)A GaAs substrate by MBE

S. Shimomura[1], K. Shinohara[1], A. Adachi[2], Y. Okamoto[3], N. Sano[4], M. Hosoda[5], K. Fujita[5], T. Watanabe[5], and S. Hiyamizu[1]

[1] Faculty of Engineering Science, Osaka University, Toyonaka, Osaka 560, Japan
Phone: +81-6-850-6457, Fax: +81-6-845-4632, e-mail shimomura@mp.es.osaka-u.ac.jp
[2] R & D Division, Nissin Electric Co. Ltd., Umezu-Takase-cho, Ukyo-ku, Kyoto 615, Japan
[3] Research and Headquarters Kubota LTD., Amagasaki, Hyogo 661, Japan.
[4] Faculty of Science, Kwansei Gakuin University, Nishinomiya, Hyogo 662, Japan
[5] ATR Optical and Radio Comm. Res. Labs., Soraku-gun, Kyoto 619-02, Japan.

Atomically flat GaAs/AlGaAs interfaces over a macroscopic area have been desired not only for application to quantum devices but also basic researches such as study on the radiative decay time of excitons in quantum wells (QWs). Since the radiative decay time of excitons in a QW is inversely proportional to the coherent volume[1)], it becomes long owing to localization caused by interface roughness. Photoluminescence (PL) spectra showed that effectively atomically flat interfaces of $GaAs/Al_{0.3}Ga_{0.7}As$ QWs was achieved over an extraordinarily large area (1 cm × 1 cm) on (411)A GaAs substrates by molecular beam epitaxy (MBE).[2,3)] In this paper, we report experimental results on luminescence and lifetime of excitons in 18 $GaAs/Al_{0.3}Ga_{0.7}As$ QWs grown on (411)A and (100) GaAs substrates by MBE.

$GaAs/Al_{0.3}Ga_{0.7}As$ QWs with well widths of L_w = 0.35, 0.6, 0.85, 1.1, 1.4, 1.65, 1.9, 2.2, 2.5, 2.85 3.2, 3.7, 4.3, 5.1 6.2 7.6, 10.3, and 15.9 nm and 20 nm thick barrier layers were simultaneously grown on (411)A and (100) GaAs substrates at 580 °C by MBE. The V/III ratio was 10 in pressure. Growth rates of GaAs and $Al_{0.3}Ga_{0.7}As$ were 1.0 and 1.43 μm/h, respectively. Figure 1 shows PL spectra from (411)A and (100) QWs at 4.2 K. Very narrow and well resolved PL peaks are shown in the spectrum of (411)A QWs. These data show that (411)A QWs have extremely flat interfaces. Since integrated luminescence intensity of each peak is as large as that for the (100) QW, non-radiative centers did not affect the luminescence for the (411)A QW. Figure 2 shows L_w-dependence of the PL decay time measured at 18K. All QWs on the (411)A substrate have shorter decay time than those on the (100) substrate. For (411)A QWs, the decay time gradually decreases from 0.83 to 0.53 ns with reducing the well thickness from 10.3 to 1.9 nm. On the other hand, the decay time of (100) QWs decreases from 0.94 to 0.72 ns and then rises from 0.72 to 0.98 ns with decreasing the well thickness from 10.3 to 1.9 nm. The ratio of the decay times of (411)A QWs and (100) QWs has a minimum value of 0.57 at a well thickness of 1.9 nm. These shorter radiative decay times of (411)A QWs indicate that (411)A QWs have much improved well thickness uniformity resulting in enhancing the coherent volume of excitons.

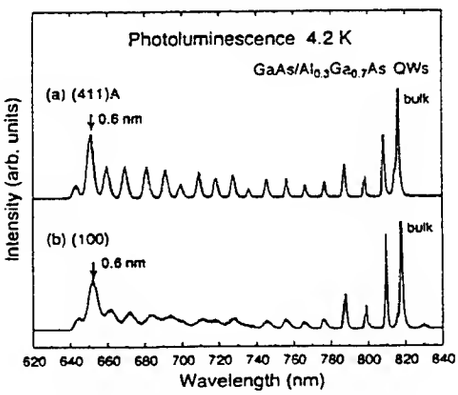

Fig. 1 PL spectra at 4.2K

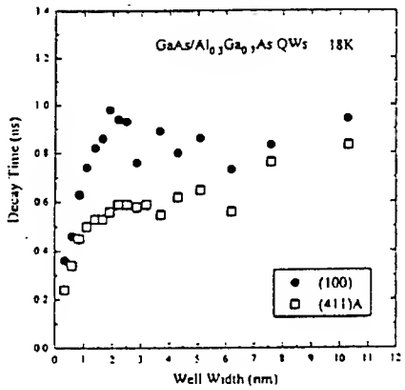

Fig. 2 PL decay time at 18K

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OPTICAL STUDIES OF LOCALISED EXCITONS IN SYMMETRIC COUPLED QUANTUM WELLS

R.J. Stone, J.G. Michels, D. Kinder, C.C. Chang, J.S. Roberts[+], R.J. Nicholas, A.M. Fox.

Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, UK.

[+]EPSRC III-V Semiconductor Facility, Dept. of Electronic and Electrical Engineering, Mappin Street, Sheffield, S1 3JD, UK.

We report novel studies of excitons in GaAs/AlGaAs symmetric coupled quantum wells (SCQWs) by far-infrared modulated photoluminescence spectroscopy (FIRMPL). This work is motivated by interest in the optical response of SCQWs at far-infrared (FIR) frequencies, for possible applications in THz detectors and emitters.

The delocalised states of SCQWs are known to be very sensitive to asymmetry due to monolayer fluctuations, which causes the wavefunctions to collapse into single well states. These localised states give rise to fine structure in the zero-magnetic field photoluminescence (PL). The measured diamagnetic shifts of these PL peaks allow us to identify both delocalised excitons and excitons which are localised by monolayer fluctuation islands.

The technique of FIRMPL measures the change in the interband PL associated with absorption of FIR radiation. We find that it is possible to pump carriers optically from the localised to the delocalised states when the FIR energy is resonant with the splitting observed in the PL (5.4 meV). This indicates that there is a coupling between excitons in spatially separated islands. A similar coupling between excitons bound to different quantum well islands has been reported by a group using time-resolved four-wave mixing to observe excitonic quantum-beats. Our experiment complements their measurements, and may allow a more detailed study of the coupling mechanisms.

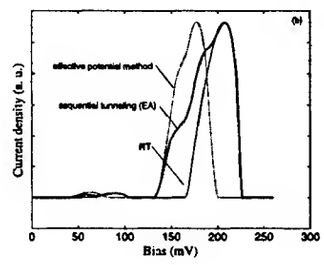
EXCITON-ASSISTED TUNNELING TRANSPORT IN THE HETEROJUNCTION MICROSTRUCTURES

Simon M. Cao* and M. Willander
Department of Physics and Measurement Technology,
Linköping Institute of Technology, S-581 83 Linköping, Sweden

Resonant tunneling (RT) in various heterojunction microstructures has been a thoughtfully investigated topic for many years. However, when both electrons and holes are involved in tunneling, the modulation of the diode current-voltage (I-V) characteristics can be significant due to the strong Coulomb interaction in the active regions of low-dimensionality. Most of all, radiative and non-radiative excitons can present in the intermediate tunneling states giving rise to additional quantum transport of carriers. This phenomenon has been observed in the tunneling current of bipolar RT diodes and unipolar heterojunction diodes coupled with external optical excitation in a few experimental investigations.

In this report, we formulate the mechanism of the exciton-assisted transitions within the framework of the Fermi golden rule. The I-V characteristics have been studied using a sequential tunneling Hamiltonian incorporated with tunneling transitions of free carriers (or free excitons) to confined excitons. The modeling can be generally evaluated via a set of coupled rate equations involving subband states of three types of particles.

We have found that the tunneling current of the exciton-assisted transitions gives a considerable contribution to the I-V spectra, but shifts towards low-field relative to the RT current. The offset is comparable to the FWHM of the dark current spectra and depends on both the quasi-fermi level of confined hole subband and the degree of confinement in the active region. The excitonic effect tails off at the high-fields associated with the gap corresponding to the exciton binding energy. Our calculations agree fairly well with the experimental result obtained in AlGaAs/GaAs RT diodes in which a pre-shoulder is revealed in the I-V curve when a light source is applied.



*Email: **mangc@ifm.liu.se**, Phone: **+46 13 281727**, Fax: **+46 13 132285**.

TUNNEL DEVICES ARE NOT YET MANUFACTURABLE

V A Wilkinson and M J Kelly,
Physics Department, University of Surrey, Guildford GU2 5XH, UK.

We describe the greater than ±20% (=unacceptable) variability in the rectifying current-voltage characteristics that occurs routinely across a wafer and between wafers in the case of a single-tunnel-barrier diode structure such as might be used as a microwave detector. Multiple batches of wafers have been grown by both MBE and MOCVD to the exceptionally tight growth specification (as implied by realistic I-V simulations) required to obtain adequate uniformity for device applications. The techniques of transmission electron microscopy, secondary ion mass spectrometry and X-ray diffraction, as currently performed routinely, all fail to give sufficiently precise data on whether the as-grown structures actually meet the growth specifications. Several other techniques (including ellipsometry and infrared absorption) have also been examined and found inadequate. Only when these techniques are pushed to the state-of-their-art do we approach the required precision. Using the same simulations referred to above, we quantify the further improvements in the growth, assessment and fabrication of tunnel device structures that are needed before an acceptable level of variation (i.e. less than ±10%) in current-voltage characteristics is achieved for practical device applications. The challenges derived here apply, a fortiori, to any mesoscopic structures proposed for devices.

Dependence of parallel hole mass on quantum well width, barrier parameters and wave function localization

U.Ekenberg

Department of Physics, Royal Institute of Technology, S-10044 Stockholm, Sweden

and

A. Ghiti

Department of Electrical and Electronic Engineering, University of Newcastle,

Newcastle-upon-Tyne NE1 7RU, United Kingdom

In two-dimensional structures the energy dispersion parallel to the layers for hole subbands depends on the complex interactions between heavy-hole and light-hole subbands. For the uppermost subband these interactions tend to raise the energy at finite values of $k_{//}$ and in this way increase the parallel mass. In order to achieve a small parallel mass it would be desirable to turn off these interactions as much as possible. So far this has mainly been achieved by introducing strain in lattice-mismatched materials, which has led to considerable improvements in the performance of lasers.

It has been suggested that in a narrow quantum well, where the subband separations are large, a reduced interaction between the subbands would lead to a smaller parallel mass for the uppermost subband. Our numerical multiband calculations show that the opposite trend actually occurs. A possible explanation for the increase of mass with decreasing well width is that the increased wave function penetration into the barriers, where the mass is higher, would lead to a higher parallel mass. However, we find that this is not the dominant contribution. In terms of second-order perturbation theory the effect of increased subband separations is more than balanced by matrix element effects. We analyze these results with the use of scaling arguments, which are exact for infinitely high barriers and lead to well-width-independent parallel masses in that case.

We finally discuss the possibility of influencing the parallel mass with a combination of strain and modulation doping such that the subbands, with which the uppermost hole subband normally interacts, have wave functions which are well separated spatially from the quantum well region.

RESOLUTION OF THE OUT -OF-ZONE SOLUTION PROBLEM IN ENVELOPE FUNCTION THEORY

M G Burt , BT Labs , Martlesham Heath, Ipswich, IP5 7RE, UK

Envelope function methods are widely used to model electron states in microstructures where single band effective mass methods are inappropriate. However, the presence of spurious, out of zone solutions pose a serious dilemma for the method[1] : the out of zone solutions appear unphysical yet including them is necessary to satisfy all the boundary conditions implied by the envelope function equations. If one ignores the out of zone solutions, either one has to be selective in which boundary conditions one is going to apply, which produces questionable results, or carry out a full wavefunction matching which is almost tantamount to a complete, direct solution of the Schroedinger equation. This paper shows how to resolve this dilemma.

In an earlier publication[2] the author has suggested that the mathematically correct procedure is to use all solutions, including out of zone solutions, generated by the envelope function equations and apply all the boundary conditions implied by them at abrupt interfaces. This procedure will be illustrated using a simple one dimensional model[3] so that the main results can be clearly presented. It will be seen that the procedure reproduces the correct wavefunction and clarifies the role of the out of zone envelope function solutions.

As a result of this work there is now a straightforward unambiguous procedure for applying the envelope function method to microstructures, a method that removes the uncertainty, but retains the simplicity of the envelope function approach.

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Valence band spectrum in pseudomorphically strained würtzite quantum wells

Yu. M. Sirenko, J. B. Jeon, K. W. Kim, and M. A. Littlejohn

Department of Electrical and Computer Engineering,
North Carolina State University, Raleigh, North Carolina 27695, U.S.A.

M. A. Stroscio

U.S. Army Research Office, Research Triangle Park, North Carolina 27709, U.S.A.

Recent progress in fabrication of blue and UV optoelectronic devices based on wide band gap nitride semiconductors has renewed interests in the details of both bulk and quantized hole spectra in würtzite materials. Since many important transport and optical properties are related to the hole behaviors near the Brillouin zone center in the form of effective masses and optical matrix elements, Γ_9, Γ_7, and Γ_7 levels of würtzite space group C_{6v}^4 must be analyzed. The strong coupling at the Γ point results in non-parabolic relations at small wave vector $\mathbf{k}$ which can be described by envelope-function formalism with a set of several Luttinger-type parameters, crystal and spin-orbit splitting energies, and deformation potential parameters.

In our previous work [1], we derived the block-diagonalized 6×6 Rashba-Sheka-Pikus (RSP) Hamiltonian of würtzite valence bands and described analytical formulation of A-, B-, and C-type holes in both bulk and quantum well case by applying unitary transformation of the basis. In this study, we discuss anisotropic and anti-crossing features of the numerically obtained valence band spectra of several würtzite-type bulk materials based on the sets of valence-band parameters which are derived from full-band calculations. We also propose a set of cubic-approximated deformation potential parameters for GaN and analyze the effect of biaxial strain on the holes spectra in nitrides. Finally, we calculate the dispersion relations and density of states for holes in pseudomorphic $Al_xGa_{1-x}N/GaN/Al_xGa_{1-x}N$ quantum wells, solving numerically the secular equation involving a 12×12 matrix. Effects of varying well width and composition ratio x are investigated. Implications of these results on optoelectronic properties of GaN quantum wells are discussed as well.

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Electron channel with high carrier mobility at the interface of isotype II broken-gap p-GaInAsSb/p-InAs single heterojuctions

M.P.Mikhailova, T.I.Voronina, T.S.Lagunova, K.D.Moiseev,

S.A.Obukhov, A.E.Rozov and Yu.P.Yakovlev

Ioffe Physical Technical Institute, RAS, St.Petersburg, 194021, Russia

We report the first observation of electron channel with high carrier mobility (u_H=50,000-70,000 cm^2/Vs) at the interface of isotype II p-GaInAsSb/p-InAs single heterojuctions with a broken-gap alignment. Weak temperature and doping level dependence of Hall mobility in the range 4.2-200K was obtained. It was an evidence that predominant carrier scattering mechanism is interface roughness. Strong Shubnikov-de Haas oscillations and anisotropy of longitudinal magnetoresistance were found in the p-p samples with various doping level of quaternary layers at T=1.5-10K and moderate magnetic field (up to B=5T). Some important parameters were evaluated from these experiments. Effective mass $m^*=0.026m_0$ equal to electron mass in InAs was found. It confirms a location of the electron channel at the InAs-side. 2D-electron concentration in the channel was $n_s \sim 3*10^{11}$ cm^{-2}, Dingle temperature (T_D) was equal to 1.7 meV and 5.0 meV at 1.5K and 4.2K respectively. Momentum relaxation time $\tau=1.5*10^{-12}$ s deduced from broadering parameter of Landau level was in a good agreement with a value found from Hall mobility measuring. Existence of electron channel at the interface was demonstrated also by scanning tunnel microscopy (STM) studing of cleavage of the p-GaInAsSb/p-InA structure in air at room temperature.

Obtained results demonstrated high quality unterface of GaInAsSb/InAs heterostructures grown by LPE on InAs substrate. Such heterostructures are very promising for creation of mid-infrared optoelectronic devices. This work was supported in part by Russian Fundamental Sciences Foundation grant N96-02 117841a.

A Novel Secular Equation for the Superlattice Envelope Function Formalism and Application to the Calculation of the Electronic Structure of Type-II InAs/$In_xGa_{1-x}Sb$ Superlattices

Frank Szmulowicz

University of Dayton Research Institute, 300 College Park Ave., Dayton, Ohio 45469-0178

A novel method is proposed for implementing the coupled-band envelope function approximation (EFA) formalism for the calculation of the electronic structure of superlattices. It is well known that the secular equations resulting from boundary-matching conditions,[1] including the transfer-matrix[2] formalism, encounter difficulties in handling fast-decaying wave function components, in particular, the so-called "wing solutions." A solution for handling such numerical problems for quantum wells was offered earlier.[3] For superlattices, the present treatment of an N coupled-band EFA formalism yields a secular equation in which the fast-decaying exponents occur only inside hyperbolic tangents and not inside exponentials. This has the benefit of eliminating numerical problems even in the case of wing solutions and long-period superlattices. Most importantly, for a multiple-band formalism, the present formalism makes it unnecessary to first find a unitary transformation to eliminate the time-reversal degeneracy of the bulk Hamiltonian.[4] At a general wavevector, the present method leads to an only 2Nx2N, Hermitian secular matrix, whose diagonalization allows to separate Kramers degenerate roots. In the case of the simple Kronig-Penney model, the present methodology recasts the eigenvalue equation into a novel form. The method will be demonstrated on the example of the technologically important semiconducting InAs/$In_xGa_{1-x}Sb$ type-II superlattice.

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Electronic structure of (311)-InAs monolayers in GaAs

Toshio Saito
Institute of Industrial Science, University of Tokyo
7-22-1 Roppongi, Minato-ku, Tokyo 106, Japan

Ultrathin InAs layers grown pseudomorphically on GaAs substrates with different orientations have attracted much attention both from fundamental and application points of view. Especially structural and optical properties of InAs layers on (311) GaAs substrates have been studied in detail experimentally, in order to investigate the electronic structures of (311)-InAs monolayer and submonolayer [1–3]. It is found that the energies of the InAs-related optical transitions depend on orientation [3].

In contrast with the detailed experimental studies, theoretical investigations on the electronic structures of (311)-InAs layers based on atomic-scale calculations, such as a tight-binding theory, have not been performed.

In this study, we theoretically investigate the electronic structures of (311)-InAs monolayers in GaAs to relate the electronic structures and the optical properties on a "high-index" substrate. We calculate the energies and wave functions of the InAs-related electron and hole levels in the GaAs band-gap, which depend on the atomic configurations of InAs layers.

The theoretical calculations are carried out by the semi-empirical tight-binding method with the sp^3s^* basis [4]. The $(GaAs)_5/(InAs)_1/(GaAs)_5$ [311] superlattice is used as a model of the (311)-InAs monolayer in GaAs. The (311)-InAs monolayers are separated by the $(GaAs)_{10}$ layers. The length of the strained In–As bonds is calculated from the lattice deformation of pseudomorphic InAs on a (311) GaAs substrate. The expressions for the lattice deformation shown by De Caro and Tapfer [5] are used for the calculation.

The present calculation shows that the (311)-InAs monolayers introduce the electron and hole levels in the GaAs band-gap, which are located slightly lower than the GaAs conduction-band edge and slightly higher than the GaAs valence-band edge, respectively. (The electron level is located 0.03 eV lower than the conduction-band edge, assuming the fractional conduction-band offset $Q_c = 0.55$ [1].) The separation between the electron and hole levels is calculated to be 1.49 eV. This value accounts for the photoluminescence peak at 1.482 eV measured by Alonso *et al.* [3] for the sample grown by molecular beam epitaxy (MBE) with the InAs thickness 1.8 Å.

The wave functions of the electron and hole levels introduced by the (311)-InAs monolayer are extended in the $(GaAs)_5/(InAs)_1/(GaAs)_5$ unit cell, showing a slightly higher amplitude around the (311)-InAs monolayer.

In conclusion, the present tight-binding calculation shows that the (311)-InAs monolayers in GaAs introduce the electron and hole levels in the band-gap, which accounts for the photoluminescence measurement [3] for the MBE-grown sample quantitatively. In the conference, the effects of InAs thickness, In redistributions, and spin-orbit coupling (which is not included in the present stage) on the electronic structures will be reported and compared with the results of the (100) case.

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Identification of Zone Boundary and Interface Phonon Recombinations in Photoluminescence from type II GaAs/AlAs Short Period Superlattices

T. Gilmour[+] , P.C. Klipstein[+], W.R. Tribe[*], G.W.Smith[$]

+ Clarendon Laboratory, Dept. of Physics, Oxford University, Parks Rd, Oxford OX1 3PU, UK
** Department of Physics, University of Sheffield, Sheffield S3 7RH, United Kingdom*
$ Defence Research Agency, St.Andrews Road, Malvern, Worcestershire WR14 3PS, UK

Due to the band alignment in GaAs/AlAs superlattices (SL) and the indirect nature of bulk AlAs, it is possible to use the quantum confinement in short period superlattices (SPSL) to engineer a type II system. This produces an electron population in the AlAs X_z level, which is spatially separated from the hole population in the GaAs Γ level, in both direct and reciprocal space. Through the interface (IF) mixing potential, interband Γ-X_z radiative transitions become allowed in SL's. This enables recombination lifetimes to be tuneable simply through variation of the SL geometry and has potential applications in optically non-linear devices. The disputed participation of some momentum conserving phonons in the radiative transitions from both X_z and X_{xy} has recently been resolved by a direct comparison, in the same samples, of the photoluminescence (PL) phonon satellite energies, with the energies of zone boundary and IF phonons determined by *first order* resonant Raman scattering, excited close to the type II or type I bandgaps respectively [1]. In this work we use a similar approach but on complementary SPSL's with period repeats of 11/8 and 8/11 monolayers (*ml*), to prove the direct participation of the GaAs IF mode in Γ-X_z recombination.

Phonons localised at the SL interfaces contribute upper and lower branches with a Frohlich electrostatic potential that is even, IF(+), or odd, IF(-), with respect to reflection in a plane bisecting each GaAs layer. In changing the *ml* composition of the SL from an 11/8 to 8/11, the IF branch parities are simply reversed. We identify this reversal through PL measurements, where coupling is only allowed to the IF(+) branch. We are also able to identify a weak additional satellite, not previously reported, between the IF(+) and LA(X) satellites. Its origin will be discussed.

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"FOLDED" ACOUSTIC MODES IN III-V ALLOYS WITH CuPt ATOMIC ORDERING

A. Hassine, J. Sapriel, P. Le Berre,

FRANCE TELECOM, Centre National d'Etudes des Télécommunications, Paris B,

Laboratoire de Bagneux, 196 Av. H. Ravera, 92225 Bagneux Cedex, France.

and Y. Monteil

Université Claude Bernard, Laboratoire de Physicochimie Minérale

43, Bd. du 11 Novembre 1918 - 68622 Villeurbanne Cedex, France

Atomic ordering in an alloy results in the spontaneous formation of a short period superlattice along a particular crystallographic direction. In the case of (001)-oriented GaInP and GaInAs layers, lattice matched to GaAs and InP, respectively, a new structure appears ($CuPt_B$-type), of trigonal symmetry, giving rise to a superlattice of alternating Ga-rich and In-rich alloy monolayers perpendicular to [111]. The superlattice structure which results from ordering shows itself through phonon mode modifications, which are here studied by means of Raman scattering. Many samples displaying different atomic ordering degrees, and preliminary characterized by polarized photoluminescence (shrinkage of the bandgap, valence band splitting) are investigated.

In this study several new Raman modes are detected at 300K and 80K, and their frequency and intensity behaviours are properly analyzed. The most striking effects are observed in the acoustic phonon frequency range (below 200 cm^{-1}) where for the first time the so-called folded longitudinal acoustic and folded transverse acoustic modes simultaneously appear in the spectra. These modes correspond to the L points of the Brillouin zone on the LA and TA branches, which become Raman active, owing to the doubling of the unit cell. Both folded acoustic modes display narrow lines (~10 cm^{-1}) superposed to the disorder induced acoustic bands DALA and DATA.

A linear chain model of superlattice along [111] without any adjustable parameter, is proposed with alternating Ga-rich and In-rich monolayer of GaInP (or GaInAs) to account for the measurements. The results of the frequency calculations are in very good agreement with the experiments concerning the folded acoustic modes in the investigated crystals, as a function of the atomic ordering and give a qualitative account of the observed optical modes behaviour.

FANO-LIKE ELECTRON-PHONON INTERFERENCE IN δ-DOPED GaAs SUPERLATTICES

Yu.A.Pusep, M.T.O.Silva, S.W. da Silva[1], J.C.Galzerani, L.M.R.Scolfaro[2], R.Enderlein[2], A.A.Quivy[2], A.P.Lima[2] and J.R.Leite[2]

DF - Universidade Federal de São Carlos, C.P.676, 13565-905 São Carlos, SP., Brasil
[1]Instituto de Física de São Carlos, Universidade de São Paulo, 13560-970, São Carlos, SP., Brasil
[2] Instituto de Física, Universidade de São Paulo, C.P. 66318, 05389-970, São Paulo, SP., Brasil

An interaction between electron excitations and LO phonons was systematically studied by Raman scattering in δ-doped GaAs superlattices. The coexistence of two types of electron-LO phonon interactions was experimentally demonstrated: the off-resonance spectra, to which the deformational potential contributes, reveal the coupling of the LO phonons with the superlattice plasmons both propagating normal to the layers (L^+ mode in Fig.1), while those taken at nearly resonance with the $E_0 + \Delta_0$ electronic transition of GaAs present the Fano-like interaction of the LO phonons with the quasicontinuum single-particle electron excitations (LO_F mode). It was shown that the Fröhlich interaction is responsible for this type of the electron - LO phonon coupling. Due to the self-consistent origin of the electron energy spectrum in δ-doped GaAs superlattices the resonance of the Fano interference was found to be strongly dependent of the electron density as well as of the excitation energy. The dependencies of the Fano profile parameter, the renormalization shift of the LO phonon frequency and the Fano linewidth parameter are determined as a function of doping concentration. The results are in good agreement with theoretical estimates based on self-consistent band structure calculations.

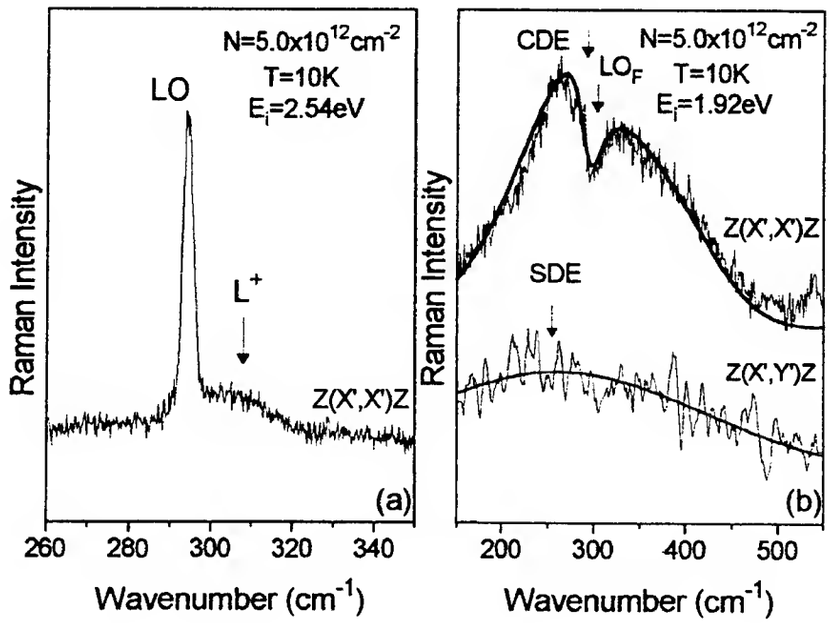

Fig.1. The Raman spectra measured out of resonance (E_L = 2.45 eV) and close to the $E_0 + \Delta_0$ resonance of GaAs (E_L = 1.92 eV) for the δ-doped GaAs superlattice with N = $5x10^{12}$ cm^{-2}.

OPTICAL-PHONON TUNNELLING AND THE BARRIER INTERFACE MODE

B.K.Ridley, O.Al-Dossary, M.Babiker and N.A. Zakhleniuk

Department of Physics, University of Essex, Colchester, UK

A recent study of the tunnelling of optical phonons across a quantum well [1] showed that this was possible for a polar mode provided its frequency coincided with that of one of the two interface modes associated with the barrier. Because of this effect LO modes in the barrier could scatter electrons in the well. In this paper we report a calculation of the total scattering rate caused by modes in the LO branch of the barrier material as a function of well-width. We show that the form of the well-width dependence and the magnitude of the scattering rate is, to an excellent approximation, the same as that predicted by the dielectric-continuum (DC) model, in which scattering is caused by barrier interface modes obeying only electrical boundary conditions. This result provides, for the first time, justification for using Fuchs-Kliewer-like interface modes, even though these do not satisfy the necessary mechanical boundary conditions at the interface. It completes a study of the applicability of the DC model to the calculation of scattering rates in a quantum well, a study that has already shown it to give good agreement with the results of the hybrid model as regards the effect of the modes in the well are concerned [2]. Our conclusion is that provided that the frequency-dependence of the coupling strength of the interface mode is correctly described, differences of detail concerning the effect of individual modes in the two models are unimportant for the total sum.

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Photoconductivity Nonlinearity at High Excitation Power in Quantum Well Infrared Photodetectors

M. Ershov, H. C. Liu† and V. Ryzhii

Computer Solid State Physics Lab., University of Aizu, Aizu-Wakamatsu, 965-80 Japan
Phone: (81-242) 37-2566, Fax: (81-242) 37-2596, Email: ershov@u-aizu.ac.jp
†Institute for Microstructural Sciences, National Research Council,
Ottawa, Ontario K1A 0R6, Canada

The photocurrent in Quantum Well Infrared Photodetectors (QWIPs) increases linearly with power of incident infrared radiation at low power levels, i.e. responsivity is constant with power. The photocurrent can be a nonlinear function of power at high power level due to a number of factors. The purpose of this paper is theoretical and experimental study of effects responsible for nonlinearity of QWIPs' photoresponse. Influence of QWIP structural parameters on nonlinear effects are discussed and design solutions to prevent the degradation of responsivity are proposed.

As has been shown in a recent paper [1], the photodetection mechanism of QWIP is associated with the redistribution of the potential in QWIP structure under the influence of infrared radiation. In QWIPs with tunneling injection mechanism this gives rise to an increase of the electric field in the first few barriers near the injecting contact and, therefore, to a decrease of field in the bulk of QW structure. At high infrared power, the modulation of the electric field produce several effects influencing the QWIP responsivity. First, the decrease of the electric field in the bulk of QW structure results in decrease of carrier drift velocity, and related degradation of responsivity. Second effect contributing to decrease of responsivity is connected with the possible strong electric field dependence of the probability of photoexcited carrier escape from the QWs [2]. Another reason for responsivity degradation is an increase of the QW capture velocity with decrease of the electric field [2]. At last, the electric field modulation is caused by the emptying of the QWs near the injecting contact by electrons (in case of n-type QWIPs) [1]. This results in a decrease of the total density of carriers in the QWs and resulting responsivity degradation. It should be stressed that these nonlinear effects can take place at infrared power density much lower than that required for saturation of inter-subband absorption.

The effects of QWIP nonlinear photoresponse with infrared power are studied both theoretically using numerical modeling and experimentally. It is shown that responsivity decreases with power for QWIPs with rectangular barriers due to the reasons discussed above. This effect is exhibited stronger for QWIPs with only a few QWs and at lower applied voltages. The degradation is much weaker in QWIPs with large (>20) number of QWs. The nonlinearity of photoresponse is strongly influenced by the structure of the injecting contact and doping level in contacts and QWs. In particular, the nonlinearity of photoconductivity can be suppressed in QWIPs with triangular emitter barrier providing thermionic carrier injection.

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Two-dimensional quantum well infrared photodetector arrays

H. C. Liu, Jianmeng Li, M. Buchanan, and Z. R. Wasilewski

Institute for Microstructural Sciences

National Research Council

Ottawa, Ontario K1A 0R6, Canada

FAX: 613 990 0202, E-mail: H.C.LIU@NRC.CA

Quantum well infrared photodetectors (QWIPs) form a new technology for the detection of infrared radiation of wavelength longer than about > 2 μm. Current research is pushing the performance of QWIPs to approach that of the industry standard infrared (IR) detectors made of HgCdTe. In addition, QWIPs have advantages in speed as demonstrated in our optical heterodyne experiments, in the ease of making multiband and multicolor detectors, and in the potential of fabricating monolithically integrated large arrays based on GaAs. We are pursuing all these areas for specific applications.

In this talk, we concentrate on the device physics related to the two-dimensional QWIP arrays. We first discuss the conventional hybrid array approach and the design of the quasi-random grating coupler for intersubband transition. We then present two novel monolithic integration approaches: (1) electronic scheme: using heterojunction bipolar transistors and (2) optoelectronic scheme: using light emitting diodes. In both schemes, the sample is grown by molecular beam epitaxy in a single growth sequence. The talk presents new experimental results, discusses the operation principles and the physics involved, and points out applications.

VALENCE-BAND STRUCTURE AND OPTICAL ABSORPTION IN P-TYPE MULTIPLE QUANTUM WELL INFRARED PHOTODETECTORS UNDER AN APPLIED ELECTRIC FIELD

R. Melliti[1], P. Tronc[1], J. Depeyrot[1], E. Mao[2], and A. Majerfeld[2]

[1] Ecole Supérieure de Physique et Chimie Industrielles, Laboratoire d'Optique Physique,
10 rue Vauquelin, 75231 Paris Cedex 05, France.

[2] Department of Electrical and Computer Engineering,
University of Colorado, Boulder, CO 80309, USA.

Intersubband absorption in p-type Multiple Quantum Well (MQW) Infrared Photodetectors subjected to an electric field parallel to the growth axis is theoretically investigated for normal incidence operation. In the present analysis, hole eigenstates are obtained exactly using Airy functions and the envelope-function approximation. In-plane dispersion relations are calculated taking into account the mixing between the heavy and light hole states. Absorption of light at normal incidence is determined from the overlap between the envelope functions of the initial and final states and the corresponding momentum matrix elements. The final states involved in the optical transitions of interest are extended states with energies close to that of the barriers.

In the presence of an electric field, the dispersion curves in the plane of the layers are shown to be highly non-parabolic and anisotropic. The first light hole band is electron like near the Γ point. We will show that the spin splitting due to the lack of inversion symmetry is an increasing function of the electric field strength. The density of states for the final states is strongly dependent on the sign and the magnitude of the voltage applied to the structure. It will be discussed that the absorption coefficient of a given well depends on its position in the structure. Finally, the calculated absorption peak wavelength of the p-MQW structure is in good agreement with the experimental absorption spectra observed for a 10-period carbon doped MQW structure ($N_a=2\times10^{19}$ cm^{-3}).

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Intersubband Electro-Optical Modulators for Near and Mid Infrared Applications

A. Sa'ar, R. Kapon, and A. Segev

Division of Applied Physics, The Fredi and Nadine Herrmann School of Applied Science, The Hebrew University of Jerusalem, Jerusalem 91904, Israel.

Tel: (972)-2-6585701 ; Fax: (972)-2-663878 ; E-mail: saar@vms.huji.ac.il

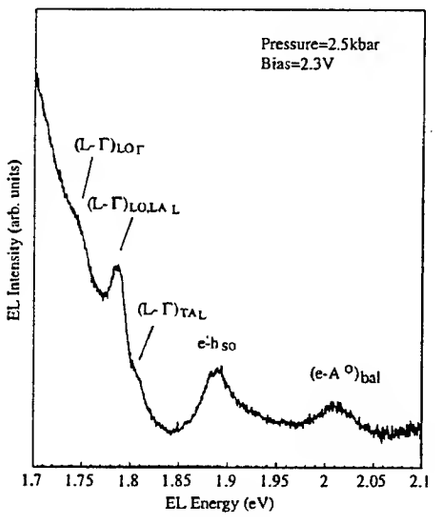
Abstract

Optical transitions between conduction subbands of asymmetrical quantum well structures can produce large second order optical nonlinearities. In particular, it is possible to engineer asymmetrical quantum well structures to have very large electro-optical coefficients. In this paper we study three alternative approaches to design and fabricate intersubband electro-optical modulators, *i.e.*, the Stark modulator, the quantum interference modulator, and the carrier density modulator. We show that electro-optical modulation that is based on the quantum interference approach is the most efficient way to produce electro-optical modulators. Furthermore, we found that the quantum interference modulator can be utilized for near infrared modulation in the 1.3 -2 μm spectral range. These modulators are almost unaffected by the linear absorption associated with intersubband transitions so that their efficiency can be very high. We propose several configurations for the development of quantum interference modulators and present preliminary experimental results that demonstrate the operation of the quantum interference modulator.

The Role of Higher Energy Bands in Hot Carrier Transport Investigated By Electroluminescence Spectroscopy

J W Cockburn[0], J J Finley[0], P Wisniewski[1], R Teissier[2], M S Skolnick[0], R Grey[3], G Hill[3] and M A Pate[3]
[0]Department of Physics, University of Sheffield, Sheffield S3 7RH, UK
[1]Unipress, Polish Academy of Sciences, Warsaw, Poland
[2]L2M, CNRS, 92225 Bagneux Cedex, France
[3]EPSRC Central Facility for III-V Materials, Sheffield S1 3JD, UK

Hot electron transport plays a key role in the operation of many high speed devices, including Gunn oscillators, heterojunction bipolar and hot electron transistors. In this paper we employ high sensitivity electroluminescence (EL) techniques to reveal the importance of interband scattering in such hot electron transport. In contrast to previous work, the use of EL techniques provides spectroscopic information on the nature of the scattering mechanisms and on their relative strengths. The experiments are carried out on single barrier GaAs-AlGaAs-GaAs heterostructures embedded in p-i-n junctions. Application of forward bias leads to injection of hot electrons (holes) through the barriers, their energy distribution being determined from their EL recombination with localised acceptor (donor) centres. A typical hot electron EL spectrum at a forward bias of 2.3V is shown in the figure. The highest energy feature $(e\text{-}A^0)_{bal}$ arises from recombination of ballistic electrons at the Γ point of the Brillouin Zone which do not undergo any intervalley transfer. The energy of this peak varies strongly with applied bias, consistent with its interpretation as a ballistic electron feature. By contrast the other features in the spectrum do not vary in energy with bias, and arise from hot electron (holes) which undergo transfer to higher energy bands. The features in the 1.75-1.82eV range arise from electrons which transfer from Γ to L, scatter to the bottom of the L minimum and then re-enter the Γ valley by zone boundary TA or LA/LO phonon emission ($(\Gamma\text{-}L)_{TA,LO/LA}$). This attribution is proved by pressure dependent EL measurements, which show a shift rate consistent with that expected from the L minimum. Analysis of the relative intensities of the $(e\text{-}A^0)_{bal}$ and the Γ-L peaks allows the fraction of electrons which undergo transfer to L to be deduced, a value of ~30% being found. We also deduce from the spectra that LA/LO scattering is the dominant L-Γ scattering process. The peak at 1.88eV ($(e\text{-}h)_{so}$) on the other hand shows a shift rate with pressure expected for a Γ-Γ transition. Its energy position is consistent with that expected for hot holes in the split-off valence band in GaAs (ΔE_{so}=355meV), and thus provides clear evidence for the importance of interband transfer of both hot holes and electrons in high electric fields of ~10^5V/cm.



NUMERICAL EVALUATION OF ENERGY LOSS RATE FOR HOT CARRIERS IN QUANTUM WELLS

Kun Huang, Bang-fen Zhu and Jian-zhong Zhang

Institute of Semiconductors, Chinese Academy of Sciences.

P. O. Box 912 Beijing 100083, China

(Fax: 86-10-2562389; Email: bfzhu@red.semi.ac.cn)

By using the microscopic phonon modes as well as the associated Fröhlich potential and the envelope functions of the electron and hole states within the multi-band **k • p** framework in the quantum well systems, numerical calculations on the energy loss rates of the hot electrons (and holes) in quantum wells are fully presented, in which an emphasis is put on the effect of the carrier density, the hot phonon population, the well width, and the phonon dispersion on the hot-carrier thermalization process in the quasi-two-dimensional system. In particular, the hot phonon effects contributed by the hot hole system and by the hot electron system are taken into account simultaneously in the present investigation. The energy relaxation process calculated by using the realistic phonon modes and that by analytical optical phonon models are compared and contrasted. Our results show that, when the sheet density of the hot carrier is increased from $10^{10}/cm^2$ to $10^{12}/cm^2$, the energy loss rate is reduced by less than one order of magnitude due to the hot-phonon effect in the quasi-static approximation. Comparison between our results and the available experimental data will be presented and discussed.

Abstract submitted for the 9-th. Int. Conf. on Superlattices, Microstructures, and Microdevices (oral presentation preferred)

PHOTOGALVANIC EFFECT IN ASYMMETRIC QUANTUM WELLS AND SUPERLATTICES

H. Schneider, S. Ehret, C. Schönbein, K. Schwarz, G. Bihlmann, and J. Fleissner
Fraunhofer-Institut für Angewandte Festkörperphysik, Tullastrasse 72,
D-79108 Freiburg, Germany
Fax: (+49) 761-5159-359; email: hschneider@iaf.fhg.de

A pronounced photo-electromagnetic force has been observed in many bulk crystals with reduced symmetry [1]. In $LiNbO_3$, this effect produces electric fields of 10^5 V/cm along the polar axis [2], strong enough to induce photorefraction and electrical breakdown. This photovoltage is due to a transition asymmetry in *k*-space upon excitation of the electron system, i.e., to a bulk *photogalvanic effect* (PGE). The phenomenon has be explained by assuming asymmetric electronic orbitals induced by an asymmetric crystal potential [1].

Semiconductor heterostructures provide a unique opportunity to study the influence of an asymmetric potential distribution on the PGE. A pronounced PGE has been observed in single-barrier quantum wells [3]. In addition to the asymmetic *k*-space distribution upon excitation, an electromagnetic force can also be obtained from an asymmetric relaxation, induced by an asymmetry of the barrier potential. The latter effect has been verified using asymetrically doped double-barrier quantum wells, in which the excitation is approximately symmetric in *k*-space, while the backrelaxation is strongly asymmetric [4]. Optimizing this effect, we have recently demonstrated highly sensitive photovoltaic intersubband photodetectors operating at 10μm infrared wavelength [5].

In this work, we report on the signatures of the PGE observed in intersubband infrared detector structures. A partial distinction between the photovoltaic contributions induced by the photoemission and by the backrelaxation has been obtained from the dependence of the PGE on the photon energy. We also investigate how emission and capture are influenced by an external electric field. Under suitable conditions, the PGE is observed to induce a sign reversal of the photocurrent.

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Multiple Wavelength Electroluminescence and Laser Generation in P-I-N Resonant Tunneling Heterostructures

A.A. Toropov, T.V. Shubina, A.V. Lebedev, B.Ya. Mel'tser, S.V. Shaposhnikov, M.G. Tkatchman, and P.S. Kop'ev

A.F. Ioffe Physico-Technical Institute, 194021 St. Petersburg, Russia

Y. Fu and M. Willander

Department of Physics and Measurement Technology, Linköping University, S-581 83 Linköping, Sweden

Simultaneous resonant injection of electrons and heavy holes was obtained in the specially designed GaAs/ $Al_{0.4}Ga_{0.6}As$ p-i-n heterostructures. The active i-region consisted of a central quantum well (QW) (16 nm) surrounded by aperiodic multiple-barrier resonant tunneling filters [1] so that electron and heavy-hole quasiminibands involving second levels in the central QW were aligned in a desired electric field. An injection laser structure was also designed with the resonant active region embedded in a graded-refractive-index optical waveguide.

The electroluminescence spectra (5-77 K) showed four peaks, which shift to higher energies for ~60 meV with increasing the forward bias from 1.5 V to 1.8 V. The resonant voltage manifested itself as a steep raise in the current and anticrossing behavior of the electroluminescence peaks. The self-consistent calculations were carried on, explaining the near-resonant spectra by interband transitions between the lowest electron level in the central well and mixed resonantly pumped levels of the heavy-hole quasiminiband. This interpretation agrees well with the expected fast electron relaxation, which is LO-phonon assisted. In contrast, the gap between the first subband and the bottom of the quasiminiband for *heavy holes* was kept below the optical phonon energy, resulting in the reduced relaxation rate and occupation of the higher subbands. Similar behavior was also observed in the laser structures, where the generation occurs involving the excited heavy-hole subbands.

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EXCITON DYNAMICS IN QUANTUM WELL MICROCAVITES

B. Sermage, S. Long, H. Eskinazi, M. Stellmacher, J. Bloch*, V. Thierry-Mieg*,

J. Y. Marzin and R. Planel*

FRANCE TELECOM, CNET, PAB, Laboratoire de Bagneux, BP 107,

92225 Bagneux Cedex, France

* L2M, CNRS, BP 107, 92225 Bagneux Cedex France

In order to study the lifetime of the mixed states resulting from the strong coupling of the excitons with the cavity mode, we have performed resonance time resolved luminescence experiments with 3 picoseconds resolution at low temperature on a microcavity containing InGaAs quantum wells. The microcavity thickness varies along the surface so that we can vary the detuning between the exciton energy E_0 and the cavity mode E_C. We observe strong resonances when the laser energy (line-width 0.4 meV) is tuned at the energies of the upper and lower states. Along the sample, the dispersion curves anticross following a polariton model with a splitting of 4.6 meV.

Under resonant excitation, the time resolved luminescence presents a fast and a slow decay. The fast decay gives the lifetime of the mixed particles which varies strongly with the detuning in agreement with a model which takes into account the escape time of the polaritons in the direction normal to the cavity (z direction), and the interaction with the acoustic phonons. The model explains also the variation of the luminescence intensity with the detuning. The slow decay comes from the return of the excitons from the reservoir.

The influence of the detection aperture and of the excitation incidence angle on the dispersion curves and on the lifetime have been observed and agree with the model.

Finally, under non resonant excitation, the intensity is smaller and we observe only the slow decay. When the excitation power is high enough ($1\,\mu J/cm^2$), we observe stimulated emission.

THEORY OF LIGHT EMISSION FROM INHOMOGENEOUSLY BROADENED EXCITONS IN SEMICONDUCTOR MICROCAVITIES

V. Savona[a], C. Weisbuch[b],

[a] *Institut de Physique Théorique, Ecole Polytechnique Fédérale, CH-1015 Lausanne, Switzerland*
[b] *Laboratoire de Physique de la Matière Condensée, Ecole Polytechnique, F-91128 Palaiseau, France*

In narrow quantum wells, interface roughness is known to produce both an inhomogeneous energy distribution of exciton levels and the destruction of the in-plane wavevector conservation. These two effects are commonly referred to as vertical and lateral disorder respectively. When the quantum well is placed in a semiconductor microcavity, the interaction between in-plane coherent excitons and cavity photons results in the polariton modes. Typical signatures of polariton modes in the strong coupling regime are the Rabi splitting of the optical spectra and the Rabi oscillations in time resolved measurements. There are, at present, few indications concerning the role of vertical and lateral disorder on microcavity polaritons. In particular, it is not well understood how the loss of in-plane coherence of the exciton states influences the polariton interaction.

In this work we develop a simple model of an inhomogeneously broadened set of exciton levels coupled to a cavity mode and to a photon bath which represents the electromagnetic field outside the cavity. The model fully accounts for the vertical disorder by means of the inhomogeneous exciton distribution, but completely disregards the lateral disorder. After an initial excitation provided by a single pulse input, light emission from the cavity is studied both in time and frequency domain. The results are used to fit the data by Norris *et al* [1] of time resolved microcavity emission under resonant excitation. The agreement between the experimental data and the results of the present work is very satisfactory and the inhomogeneous energy broadening – the only free parameter of the theory – obtained by the fit is 3.5 meV, as expected for the sample under investigation [2].

The conclusion of the present analysis is that a model which includes only the effect of vertical disorder accounts very well for the light emission under resonant excitation. Our interpretation is that the initial excitation pulse creates an in-plane coherent excitation. In the following evolution, the interaction with in-plane coherent photons prevents the initial excitation from losing the in-plane coherence. In addition, it is shown that time resolved measurements provide more informations than the corresponding frequency resolved ones. In particular, we show how, by means of the present model, the contributions of homogeneous, inhomogeneous and cavity broadenings can be distinguished in a set of time resolved data.

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Relaxation of microcavity polaritons

J. Wainstain, G. Cassabois, Ph. Roussignol, C. Delalande, M. Voos (a); F. Tassone (b);
R. Houdré, R.P. Stanley and U. Oesterle (c)

In a microcavity exhibiting the strong coupling behaviour where a Rabi splitting occurs, the eigenstates are microcavity polariton modes. The relaxation of excitation and the radiative recombination are modified with respect to the bare QW case.

Time-resolved photoluminescence in the 10-100K range is performed in normal observation of the two polariton modes either in non resonant excitation and, for the first time, in resonant excitation by following the angle-dependent polariton dispersion relations.

The experimental results are compared to a theoretical simulation of the polariton dynamics based on calculated radiative recombination rates and scattering rates with acoustic phonons. The complex structure of the DBR mirrors is taken into account in the simulation.

The results show that the leaky modes are the main sink of radiation, which explains the QW like behaviour of the decay times, at least for non-resonant excitation. At negative detuning, the long photoluminescence rise time of the low energy cavity-like polariton branch when exciting on the high energy exciton-like polariton branch, and the biexponential decay when observation and excitation are provided on the low energy cavity-like polariton mode are measured experimentally. The same dynamics at short times is also found theoretically but the agreement is only qualitative. The additional effects due to disorder in the QW structure, not included in the numerical simulation, are discussed.

(a) Laboratoire de Physique de la Matière Condensée de l'Ecole Normale Supérieure, 24 rue Lhomond, F-75005 Paris (France); b) Institut de Physique Théorique, Ecole Polytechnique Fédérale, CH-1015 Lausanne (Switzerland); (c) Institut de Micro- et Optoélectronique, Ecole Polytechnique Fédérale, CH-1015 Lausanne (Switzerland).

EMISSION OF INTERFACE MODES BY DIPOLES IN PHOTONIC CRYSTALS

M. Babiker, A. Kamli, N. Enfati and A. Al-Hajry
Department of Physics, University of Essex, Colchester C04 3SQ, UK.
email: babiker@essex.ac.uk fax +44 1206 873598

Photonic band-gap structures composed of dispersive materials are discussed with special emphasis on polar systems and on one-dimensionally periodic structures. The problem of electromagnetic field quantisation in dispersive inhomogeneous media characterised by real frequency-dependent dielectric functions is first addressed. It is then pointed out that the quantised electromagnetic fields of such structures include interface modes that can strongly influence dipole relaxation via a $\mathbf{d}.\mathbf{E}$ interaction. An electric dipole located in a photonic crystal structure can couple strongly to the interface polar optical modes if its natural frequency Ω is at near resonance with the reststrahl band of the host materials. The relaxation rates of the dipole due to emission of interface modes are displayed for varying dipole position and also when Ω is varied for a given position. The results strongly indicate the involvement of band edge effects for the interface modes in an analogous manner to enhancement effects in the optical region of the 1D band-gap material.

PHOTONIC BAND GAP EFFECT IN A SOLID STATE CLUSTER LATTICE

E.P.Petrov[1], A.N.Rubinov[1], V.N.Bogomolov[2], A.V.Prokofiev[2], S.M.Samoilovich[2], A.M.Kapitonov[1], I.N.Germanenko[1], and S.V.Gaponenko[1]

[1]B.I.Stepanov Institute of Physics, Academy of Sciences of Belarus, 70 F.Skaryna Ave., Minsk 220072, Belarus

[2]A.F.Ioffe Physico-Technical Institute of the Russian Academy of Sciences, 26 Politekhnicheskaya St., St.-Petersburg 194021, Russia

In this contribution we report on the photonic band gap (PBG) effect in the visible spectral range in cluster lattices built of closely packed silica spherical clusters known as artificial opals. The PBG effect manifests itself in optical transmission spectra of opals and fluorescence spectra and fluorescence decay kinetics of dye molecules embedded in the opal matrix. In accordance with theoretical predictions, cluster lattices investigated do exhibit a dip in transmission spectra. The spectral position and the depth of the dip are dependent on the lattice period and the ratio of the refractive indices of silica spheres and of the medium embedded in voids. We examined fluorescence spectra and decay kinetics of dye molecules (Rhodamine 6G) embedded in opal. The fluorescence spectrum of the dye in the opal matrix shows an observation angle–dependent dip providing an additional confirmation of the PBG effect. When the dip of the opal sample overlaps the fluorescence spectrum of the dye, the fluorescence decay was found to be ~1.5 times slower compared to the fluorescence decay of the similar sample whose dip is located in the other spectral region.

Transmittance antiresonances, longitudinal resonances, and large photonic gaps in periodically modulated waveguides

P. Vasilopoulos* and R. Akis**

* Concordia University, Department of Physics, 1455 de Maisonneuve Blvd O, Montreal, Quebec, Canada, H3G 1M8

** Center for Solid State Electronics Research, Arizona State University, Tempe AZ, USA, 85287-6206

Light transmission is studied through complex-unit waveguides with or without stubs attached to them periodically. The transmittance through **stubless** waveguides of width a, with periodic dielectric contrast corresponding to the two *different* subunits, exhibits *longitudinal resonances* due to bound states trapped in individual sub-units that disappear when the optical lengths of the latter are made sufficiently long. The resulting gaps can be significantly larger than those for the individual sub-units. On the other hand, **stubbed** waveguides can have bound states trapped in the stubs that may result in transmittance *resonances in the gaps* and *antiresonances within the bands* that can be made to widen into *new* bands and gaps. The photonic gaps of the **stubbed** waveguides, with or without dielectric contrast, can be *several times larger* than those of the maximum one-dimensional *quarter-wave* structure for sufficiently short width *a*. This increase results from *destructive* interference between waves propagating along the main waveguide and those reflected from the stubs. Distributed-feedback-laser stubbed structures, of stub length *s* comparable to *a*, show a quality factor that is *much higher* than that of conventional *weakly corrugated* waveguides A similar quality factor is obtained for **stubless** waveguide structures with periodic dielectric contrast.

X^+ excitons in CdTe-CdMgTe modulation-doped quantum wells.

Y.Merle d'Aubigné, A.Haury, A.Arnoult, V.A.Chitta, J.Cibert, S.Tatarenko, A.Wasiela,

Laboratoire de Spectrométrie Physique, CNRS et Université Joseph Fourier - Grenoble, BP 87, 38402 St Martin d'Hères Cedex, France

Recently charged excitons (X^-, two electrons bound to one hole, and X^+, two holes and one electron) have been found to be a characteristic feature of a two-dimensional carrier gas at low density. X^- excitons have been observed first in n-doped CdTe-CdZnTe quantum wells (QWs) [K.Kheng *et al.*, Phys. Rev. Lett. **71** (1993) 1752], then both X^- and X^+ excitons have been described in GaAs QWs. II-VI CdTe QWs are particularly favorable for studying charged excitons for two reasons : the binding energies are quite large, and transparent substrates allow quantitative transmission measurements.

We have grown CdTe QWs by molecular beam epitaxy, with nitrogen-doped CdZnMgTe barriers. Capacitance-voltage profiles confirm the localization of the doping in the barriers and the transfer of holes across the spacer layer into the QWs, due to the significant valence band offset present in the CdTe-MgTe system.

Undoped samples exhibit the free exciton, X, and, due to residual n-type doping, X^-. In remotely p-doped QWs we observe the X and X^+ excitons in photoluminescence and transmission spectra: The X^+ line is identified in the low-temperature transmission spectra by its σ^- polarization when a magnetic field is applied perpendicular to the QW : this polarization agrees with the initial state being formed of a hole (i.e., the transition is $h \rightarrow h+h+e$). From the thermal variation of the polarization rate, we deduce the Lande factor of the heavy hole ($g=-0.4$ in a 8nm QW). This value agrees with the Zeeman splitting measured on the exciton (taking for the electron the known value $g=-1.6$ for CdTe). The binding energy of this X^+ exciton (3meV in a 8nm QW) is considerably smaller than the localization energy of the exciton on the neutral acceptor (9meV for nitrogen at the center of CdTe-CdZnTe QWs) and very close to that of X^-.

For higher hole densities band-to-band transitions are observed and characterized by the Fermi-edge singularity and the Moss-Burstein shift. Applying a magnetic field reveals excited states and the transition of the 2D hole gas to the insulating state, characterized by the reappearance of the X^+ exciton.

Excited states of the negatively charged exciton X^- in wide modulation-doped CdTe/CdZnTe quantum wells.

K. Kheng [a], R.T. Cox [a], L. Gauthier [a], T. Baron [b]

[a] *CEA-Grenoble/DRFMC, 17 av. des Martyrs 38054 Grenoble-Cedex 9, France*
[b] *Laboratoire de Spectrométrie Physique, CNRS/Université J. Fourier, Grenoble*

Optical studies of the two dimensional electron gas in the low electron concentration regime formed by remotely doping the barriers (modulation-doping) of a semiconductor quantum well have led to the identification of the negatively charged exciton X^- [1]. The CdTe/CdZnTe system is well suited for the investigation of this new species X^- because, first, the exciton binding energy is rather high and, second, the built-in biaxial strain splits the degeneracy of the valence band maximun into two decoupled heavy hole and light hole states making it easier to intepret magnetic splittings and polarisation effects. These two characteristics of the CdTe/CdZnTe system also allow clear observation of exciton centre-of-mass quantization in wide, undoped quantum wells.

We have studied a modulation-doped, 350Å wide $CdTe/Cd_{1-x}Zn_xTe$ (x=0.12) quantum well structure. The sample was MBE-grown and planar doped with indium donors in the barriers at spacer distance s=250Å from the well edges. The electron concentation is $\approx 2\ 10^{11} cm^{-2}$. Only the first subband of the quantum well is populated with electrons.

Magneto-transmission measurements show the Fermi Edge Singularity feature at zero magnetic field and inter-Landau-level transitions at low field. High fields induce a metal to insulator transition. In the insulating state, the negatively charged exciton and the neutral exciton become stable and their lines appear in the absorption spectra. We observe not just one line for each species but a series of lines associated with the centre-of-mass quantization of the neutral exciton and *also* a series of lines attributed to excited states of X^- because the latter have the polarisation caracteristics of X^-. (The absorption line X^- is circularly polarised at high field and low temperature because of the magnetic splitting of the electron in the initial state of the transition that creates X^-.) These excited states of X^- do not correspond to quantization of the motion of the centre-of-mass of X^- in the wide quantum well but rather to an electron attached to a quantized exciton.

Centre-of-mass quantization of the exciton means that the momentum of its centre-of-mass is quantized in the growth direction to discrete values N=1, 2, 3, ... Comparison with an undoped sample shows a parity effect: the intensity of lines X corresponding to even values of N have strongly decreased when the electrons are introduced in the well.

The intensity of lines X^- relative to that of lines X decreases with increasing N. This result is interpreted by the expansion of the exciton envelope fonction in pairs of electron-heavy hole subbands: the lowest exciton states are the most perturbed by the electrons occupying the first subband.

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« In-well screening of the piezoelectric field in <111> CdTe/CdMnTe quantum wells by photogenerated carriers »

E. Vanelle, D. Block, J. Cibert and R. Romestain,

Laboratoire de Spectrométrie Physique, Université J. Fourier de Grenoble et CNRS (URA 8),

BP 87, F38402 Saint-Martin d'Hères, France

J.P. Likforman and A. Alexandrou

Laboratoire d'Optique Appliquée, ENSTA-Ecole Polytechnique et CNRS (URA 1406)

F91120 Palaiseau, France

In the past few years a particular attention has been paid to Quantum Wells (QWs) which exhibit an internal piezoelectric (PZ) field. Such a configuration is very interesting for nonlinear optics by the possibility of bandgap energy modulation by PZ field screening. Indeed, the PZ field spatially separates electrons and holes at each side of the QW resulting in an initially red shift of the transition energy of about 50 meV; therefore a blueshift occurs when the PZ field is screened.

All-optical devices can be based on the screening of the PZ field by photogenerated carriers. We have performed time-resolved luminescence and transmission experiments on II-VI CdTe/CdMnTe <111> QWs (maximum injection $\approx 10^{12}$ cm^{-2}). Blueshifts of the fundamental excitonic transition energy of about 10 meV have been observed. The blueshift rise time is ultrafast (below the subpicosecond resolution) and the decay is driven by the excitonic lifetime (nanosecond). A complete theoretical modelling of the screening, including excitonic effects and inhomogeneity, allows us to unambiguously attribute these blueshifts to an in-well screening of the PZ field by the photogenerated carriers, and to study the feasibility of a high-speed optical modulator. This in-well screening can be opposed to the slower out-of-well screening reported in <111> GaInAs/GaAs heterostructures.

We also demonstrate the particular behavior of excitons in such asymmetric QWs. In comparable III-V structures the binding energy of excitons is very small ($\approx$ 3 meV) and excitons are easily ionized as the carrier density increases. In CdTe/CdMnTe QWs, their binding energy is large enough ($\approx$ 10 meV) to let them play a major role in the screening.

COHERENT PATTERNS AND SELF-FOCUSING OF ELECTRONS BY A THIN NONLINEAR BARRIER

O. M. Bulashenko,[1,2] V. A. Kochelap,[2] and L. L. Bonilla[1]

[1] *Universidad Carlos III de Madrid, Butarque 15, E-28911 Leganés, Spain*

[2] *Institute of Semiconductor Physics, National Academy of Sciences, Kiev 252650, Ukraine*

Coherent processes in semiconductor nanostructures have attracted considerable interest during the last years. In this contribution we predict new nonlinear phenomena – spontaneous formation of coherent spatial patterns in semiconductor heterostructures.

Electron transport across a planar thin nonlinear layer where the potential depends self-consistently on the wave function has been studied. The nonlinear layer is considered to be a quantum barrier formed by a semimagnetic material like CdMnTe or HgCdMnTe embedded in CdTe. The nonlinearity is caused by the exchange interaction between the electron spin and the magnetic impurities inside the barrier. While the previous studies have been restricted to one-dimensional situations, when longitudinal and transverse degrees of freedom were assumed to be decoupled, we consider the fully multidimensional tunneling model.

We show that the additional space dimensions open up the possibility of spontaneous pattern formation in transversal directions. In particular, we demonstrate that when the amplitude of the incident electron wave (electron flux) exceeds a certain threshold, the electrons spontaneously induce polarization of the magnetic ions in the layer (magnetopolaronic effect) in the form of the soliton (antisoliton) and, then, diffract on it due to the nonlinear feedback. It is demonstrated that the soliton-shaped polarization causes self-focusing of the incident wave into a "beam" with a maximum of intensity outside the barrier. On the other hand, the antisoliton-shaped polarization splits the transmitted wave in two "beams", with a suppressed trace between them.

Note that we have considered as an example the semimagnetic quantum barrier although the obtained results are quite general and could be applicable to heterostructures with other mechanisms of the nonlinearity (electron-phonon coupling, electron-electron Hartree interaction, etc.). Numerical estimates for particular structures have been performed. Our results are believed to be of interest from the point of view of both theory and applications.

Carrier spin-polarization near the Fermi level in n-modulation doped AlGaAs/InGaAs/GaAs quantum well

A.L.C. Triques[1], F. Iikawa[1], M. Z. Maialle[2], J.A. Brum[1], R.G. Pereira[1], and G. Borghs[3]
[1]- *IFGW-UNICAMP, C.P.:6165, 13083-970 Campinas-SP, Brazil*
[2]- *DFFA-Universidade São Francisco, 13251-900 Itatiba-SP, Brazil*
[3]- *IMEC, Kapeldreef 75, B-3001, Leuven, Belgium*

We present CW spin-polarization measurements in n-type modulation doped $Al_{0.25}Ga_{0.75}As/In_{0.2}Ga_{0.8}As/GaAs$ strained layer single quantum well (QW). The QW shows a high two-dimensional (2D) electron gas density ($N_{2D} \sim 2 \times 10^{12}$ cm^{-2}) and the Fermi level is near the second subband which is marginally occupied. We investigated the degree of polarization as a function of excitation and detection energies using low temperature photoluminescence (PL) and photoluminescence excitation (PLE) techniques with circular polarized light.

The PL spectra show two peaks corresponding to the transitions from the 1st and 2nd electron subbands to the 1st heavy hole one. We observe a strong spin polarization for excitation energies slightly above the 2nd subband. The polarization decreases for higher excitation energies. This result is mainly attributed to heavy hole polarization. Since the light- and heavy-hole subbands are well separated in energy in this system, the hole mixing is weak, making it difficult for the hole to flip its spin.

A striking feature in our results is the higher degree of polarization observed when the PL is detected near the Fermi energy. In the 1st subband the electrons are unpolarized due to the high 2D electron density. The 2nd subband, however, is slightly occupied. Therefore, this increase of polarization is an evidence that the electrons in the 2nd subband remain polarized and are not affected by the presence of the electron gas in the 1st subband.

This is a very interesting system for spin-polarization investigation since it includes simultaneously two different situation: hole spin-polarization in the presence of a high electron density and both hole and electron spin-polarization for low electron density.

Resonant Tunnelling Between Localised and Extended States in Coupled Quantum Elbows

T.M. Fromhold, P. Hawrylak*, A. Nogaret, M.J. Gompertz, P.C. Main,
L. Eaves, F.W. Sheard and P.B. Wilkinson

Department of Physics, University of Nottingham, Nottingham NG7 2RD, UK
**Institute for Microstructural Sciences,*
National Research Council of Canada, Ottawa, Canada K1A 0R6

We have investigated sub-micron resonant tunnelling diodes (RTDs) with cross-sections shaped like a square loop (Fig. 1). The two potential barriers are chosen to have different widths so that the charge build-up in the quantum well depends on the direction of the applied bias voltage. Under forward bias (collector barrier thicker than the emitter barrier) a coulomb blockade staircase is observed in the current-voltage characteristics *I(V)*. This provides direct evidence for the existence of zero-dimensional (0D) quantum dot-like states localised at the elbows of the square loop. The spatial extent of these 0D states can be estimated from the voltage period of the Coulomb blockade staircase, and is found to be consistent with the area of a single elbow.

Under reverse bias, the occupancies of the quantum well states are close to zero. The resonant peaks observed in the *I(V)* characteristics therefore provide a direct measure of the energy level spectrum of the quantised states in the emitter elbow. When a magnetic field is applied perpendicular to the layer interfaces, two distinct series of resonant peaks are observed in *I(V)*. These resonances originate from spectral fluctuations in the emitter elbow. However, in the experiments, there are typically 10-20 electrons in the emitter elbow and 1-5 electrons in the quantum well elbow. Consequently, a quantitative interpretation of the observed resonant features requires calculations which include the many body interactions between the confined electrons.

We have undertaken detailed analytical and numerical calculations of the one- and several-electron eigenstates in the emitter and quantum well elbows of the RTD, including the effects of a magnetic field applied normal to the plane of the layers. Our calculations show that in the experimental energy regime, the eigenstates of the quantum elbows are a complicated mixture of extended states and localised dot-like states. The probability distributions of individual eigenstates are often highly irregular. Consequently, selection rules play an important role in the resonant tunnelling process and control the amplitudes of the resonant peaks. Our calculations enable us to give a physical interpretation of the experimental data in both the reverse bias and Coulomb blockade regimes.

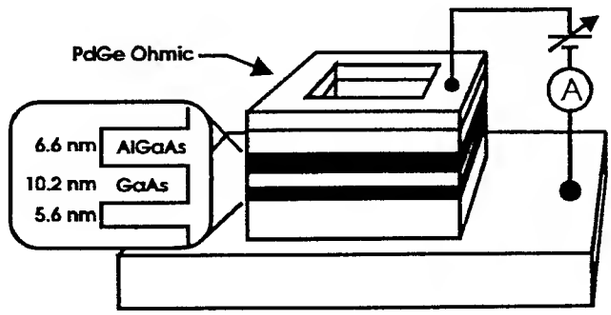

Fig. 1 Schematic diagram of the RTD. The central square hole is etched through both barriers (black) and the quantum well (layer structure shown inset) which have a square loop cross-section.

SPIN-ORBIT INTERACTION SIGN MANIFESTATION IN QUANTUM CYLINDER CONDUCTANCE

A.V.Chaplik, D.A.Romanov, L.I.Magarill

Institute of Semiconductor Physics, 63090, Novosibirsk, Russia

Quasi-two-dimensional electron systems in asymmetric quantum wells are known to contain a specific spin-orbit (SO) term in the Hamiltonian (see [1, 2]) $V_{SO} = \alpha[\hat{\boldsymbol{\sigma}}, \hat{\mathbf{p}}]\mathbf{n}$ where $\hat{\sigma}_i$ are the Pauli matrices, $\mathbf{n}$ is the normal direction. Though the constant α and its sign are determined by the atomic structure of the heterojunction, in plane systems the electron energy spectrum occurs to depend only on α^2 .

However, if the 2D electron system forms a curved surface (for example, a cylinder) two opposite directions of the normal are no longer equivalent. This surcumstance may lead to different energy spectra depending on whether the electrons occupy inner or outer surface of the cylinder.

In the present paper we have theoretically investigated this difference in a model of the circular cylinder. We have obtained the explicit analytical expression for the electron energy spectrum in the presence of the SO interaction:

$$\varepsilon_{n\sigma p} = \frac{p^2}{2m} + B\left[\left(n+\frac{\sigma}{2}\right)^2 + \frac{1-2\Lambda}{4} - \sigma\cdot\mathrm{sgn}\left(n+\frac{\sigma}{2}\right)\sqrt{\left(n+\frac{\sigma}{2}\right)^2\left(1-\Lambda\right)^2+\left(\frac{pR}{\hbar}\right)^2}\ \right],$$

where $B = \hbar^2/2mR^2$, $\Lambda = 2m\alpha R/\hbar$, R is the cylinder radius, $n = 0, \pm1, \pm2...$, $\sigma = \pm1$ is the quantum number which labels two branches of spin split spectrum. Note, that Λ here is not a small parameter. This spectrum determines the cylinder longitudinal ballistic conductance as a staircase-like function of the Fermi momentum. In the considered situation the steps modify essentially their form as compared with the problem without SO interaction. According to the above expression, this modification depends on the α sign.

We have investigated the transition from the cylinder to strip-like quantum wire. We have found out that in the latter case the mentioned above modification vanishes. This demonstrates the topological character of the discussed effect (Berry phase?). We suggest experiments to observe the SO related effects in semiconductor heterostructure quantum cylinders.

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PHOTOVOLTAIC EFFECT IN A SUBMICRON BALLISTIC RING.

A.A.Bykov, L.V.Litvin, N.T.Moshegov, A.I.Toropov

Institute of Semiconductor Physics, Novosibirsk, Russia.

We studied photovoltaic effect in ballistic ring, generated by microwave irradiation. We compared microwave emf signal and resistance dependencies on the magnetic field and found, that photovoltaic effect originates from the asymmetry of the ballistic nonequillibrium electrons motion in the direction of the left and right ohmic contacts in the microstructure due to the geometric nonideality.

Measurements were performed at T=1.6-4.2 K in the frequency range 9-78 GHz in a magnetic fields up to 2T. The samples were submicron rings with effective radius (0.3-0.5)μm. Devices were fabricated on the basis of AlGaAs/GaAs MBE heterostructures by means of electron lithography and reactive ion etching. The two-dimensional electron gas mobility at T= 4.2 K was $(4\text{-}6)\times10^5$ cm^2 /Vs, the electron density $(3\text{-}5)\times10^{11}$ cm^{-2} . Microwave emf in ballistic ring as a function of magnetic field reveals periodic (h/e) and aperiodic oscillations. We found, that aperiodic resistance and emf fluctuations are correlated with each other at frequency 9 GHz. The amplitude of the aperiodic component of the magnetoresistance fluctuations was not changed with the decrease in temperature, however, amplitude of the Aharonov-Bohm oscillations is increased. This temperature dependence indicates, that aperiodic fluctuations of the resistance and photovoltaic effect in the electron ballistic motion in our samples is determined by the commensurability effect of the electron ballistic motion. This assumption is also supported by the strong frequency dependence of the microwave emf originated from the changing in the resonance condition of the nonequillibrium electrons motion with the frequency variation .

Thus, the photovoltaic effect has been studied in the submicron rings at the first time. The qualitative explanation of the mechanism which is responsible for the aperiodic and h/e oscillations in microwave emf in the submicron ring at ballistic regime has been done.

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MAGNETO-TRANSPORT OF ELECTRONS IN A NON-HOMOGENEOUS MAGNETIC FIELD

S. M. Badalian, I. S. Ibrahim and F. M. Peeters

Department of Physics, University of Antwerp, B-2610 Antwerpen, Belgium

The transport properties of a two-dimensional electron gas (2DEG) subjected to a spatial dependent perpendicular magnetic field is calculated. We take the magnetic field profile $B_z(x)=0$ ($0<x<a$ and $b<x<L$) and $B_z(x)=B_0$ ($a<x<b$) which is appropriate to the experimental situation of Ref. 1 where the non-homogeneous magnetic field was produced by varying the topography of a non-planar 2DEG grown at a GaAs/AlGaAs heterojunction.

We solve the 2D Laplace equation for a 2DEG in the above magnetic field profile with specific boundary conditions. Conformal mapping method [2] is used to obtain the spatial electric, current and potential profiles in the 2D-plane. From this we obtain the Hall resistance and magnetoresistance which we compare with the experimental results of Ref. 1.

This classical theory is able to explain the overall magnetic field behavior. We introduced a magnetic field dependent electron relaxation time [3] in order to describe the Shubnikov-de Haas oscillations in the resistance.

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Mesoscopic conductance fluctuations of a two-dimensional electron gas in a one-dimensional lattice of antidots

M.V. Budantsev, Z.D. Kvon, A.G. Pogosov, L.V. Litvin.
Institute of Semiconductor Physics, Novosibirsk, Russia

Magnetoresistance of a 2D electron gas in a one-dimensional lattice of antidots has been studied experimentally, for the first time.

The test samples were prepared from a GaAs/AlGaAs heterojunction, in which the mobility of the 2D electron gas was $\mu=60\times10^3 cm^2/(Vs)$, and the electron concentration was $n_s=9\times10^{11} cm^2$. One-dimensional lattice of antidots was produced by electron lithography and reactive ion etching. It was placed at the center of a channel, lithographic width of which was W=800 nm. The period of the lattice was d=500 nm, the radius of antidots a=100 nm and the length of system was 8μm.

Measurements were carried out at the temperatures from 1,9 to 4,2 K and in magnetic fields from 0 to 8 T. The magnetoresistance of the samples had a form of mesoscopic fluctuations with the amplitude increasing with the decreasing of temperature. At the low temperatures in the spectrum of the fluctuations a pronounced periodic component with period $\Delta B\approx0,02$ T appeared.

That corresponds to the increasing of magnetic flux by quantum h/e through the area of a unit cell of the lattice. Arising of the periodic component in magnetoresistance in electron billiards can be explained by the interference of electrons, following the selfcrossing paths. As show the calculations we performed, there is anomalous distribution of selfcrossing paths on embraced areas S with large maximum at the area of a unit cell in these systems. With lowering temperatures down, when length of phase coherence becomes comparable to the sizes of the unit sell, this distribution cause to Aharonov-Bohm oscillations.

The Ultimate Scaling Limit of Semiconductor-based Transistors

W. Zhang,* C. H. Yang,* and M. J. Yang†

*Electrical Engineering Department, University of Maryland, College Park, MD 20742, U. S. A.

†Naval Research Laboratory, Washington, D. C. 20375, U. S. A.

Scaling the conventional MOSFETs is expected to reach a fundamental limit when the effective channel length is less than ≈ 100 nm. Beyond this limit, the Short-Channel Effect will gradually dominate. We report our recent finding on two new quantum transistors, one silicon-based and the other InAs-based. The silicon-based quantum MOSFET is similar to a conventional MOSFET, but now the source and the drain are replaced by shallow silicides. Along the source-channel-drain path, electrons experience an abrupt potential barrier resulting from the back-to-back Schottky barriers. However, when the gate induces electrons in the channel, quantum tunneling dominates, and the source-drain conductance becomes high. Using a quantum tunneling MOSFET with 10 nm channel length for an example, we will show computer simulations in two-dimensions on the transistor characteristics, and discuss the most recent experimental progresses in realizing this new transistor. We have also investigated another transistor structure using InAs single quantum well and AlSb barriers. Based on the unique Fermi level pinning property at the surface of InAs and the large bandgap offset between InAs and AlSb, we have experimentally demonstrated the possibility of scaling the lateral dimension of this field-effect transistor to ≈10 nm. Again, numerical simulation and most recent experimental results will be reviewed. In summary, we will present the operating principle, numerical modeling results, and experimental findings of two new types of transistors. Both are based on quantum tunneling, and their lateral dimension can in principle be downscaled to nanometers. *The presently perceived scaling limit in channel length can thus be pushed by another order of magnitude*. A comparison with the single-electronics approach, in terms of transistor characteristics and practical manufacturability issues, will also be given.

INVESTIGATION OF DELTA-DOPED QUANTUM WELLS FOR POWER FET APPLICATIONS

N. J. Woods (a), J. M. Roberts (b), J. J. Harris (b), and M. Hopkinson ©

(a) Semiconductor Material IRC, Imperial College, London, SW7 2BZ.
(b) Semiconductor Material IRC, Dept. of Electronic and Electrical Engeneering, University College, London, WC1E 7JE.
(c) III-V Central Facility, Dept. of Electronic and Electrical Engeneering, University of Sheffield, S1 3JD.

A systematic study of the effects of material composition and Si delta-(∂-) doping plane position on the transport properties of several ∂-doped GaAs/AlGaAs and InGaAs/InP quantum well (QW) structures is presented. The intention is to determine the design rules for high carrier concentration, high mobility structures suitable for high frequency power FET applications such as microwave generation.

Previous works on ∂-doped structures have generally shown low carrier mobilities [1, 2] due to the high levels of ionised impurity scattering present, a result of the spatial coincidence of the electrons and donors. Self-consistent Poisson-Schrödinger modelling suggests that by edge doping the QW an electron-donor separation is created which decreases the amount of ionised impurity scattering thereby improving carrier mobilities. Such separations can be further increased by compositionally grading the QW. The digital alloying technique has been used to produce these graded edge ∂-doped $In_xGa_{1-x}As$ QWs.

Measurements have shown a 13% mobility (μ) improvement in the edge ∂-doped QWs over the uniformly doped and centre ∂-doped structures. Also observed is an 11% improvement in the electron saturation drift velocity (v_s) in the same sample set. Improvements in mobility of 100% (to 2300 cm^2/Vs) and 67% in saturation drift velocity (to $1.77x10^7cm/s$) have been observed in the digitally graded, strain balanced, $In_xGa_{1-x}As$ structures when compared to the lattice matched edge ∂-doped $In_{0.53}Ga_{0.47}As/InP$ QWs. Increasing the linearity of the grade is expected to increase electron-donor separations resulting in further enhanced carrier mobilities and saturation drift velocities. The saturation drift velocity results are the best we have seen for such highly doped structures (the carrier concentration was determined as $4x10^{12}cm^{-2}$).

Investigation of the high field data has revealed a relationship between v_s and μ of the form $v_s \propto \mu^{0.8\pm0.4}$. This relationship underlines the impact a high carrier mobility has on the high frequency operation of a transistor device.

X-ray diffraction data performed on the digitally graded structures is also presented confirming that these structures are strain balanced.

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MULTISTABLE CURRENT-VOLTAGE CHARACTERISTICS AS FINGERPRINTS OF GROWTH-RELATED IMPERFECTIONS IN SEMICONDUCTOR SUPERLATTICES

G. Schwarz, M. Patra, F. Prengel, and E. Schöll
Institut für Theoretische Physik, Technische Universität Berlin,
Hardenbergstraße 36, 10623 Berlin, Germany
email: schwarz@physik.tu-berlin.de

Weakly coupled, doped semiconductor superlattices exhibit spontaneous formation of electric-field domains if a large voltage is applied in the growth direction. This results in static multistable current-voltage characteristics consisting of a sequence of branches whose number is roughly equal to the number of superlattice periods [1].

We use a one-dimensional sequential transport model based on resonant and nonresonant tunnelling between neighbouring wells to show that the lengths and positions of the current branches are extremely sensitive to deviations of the actual superlattice structure from perfect periodicity. We demonstrate that the inclusion of growth-related imperfections (varying structural parameters and doping density) into the model does not only lead to a considerably better agreement with experimental results, but also that the current-voltage characteristic of a sample in turn represents a "fingerprint" of its individual sequence of fluctuations. It is therefore possible to estimate the degree of microscopic disorder from the global current-voltage characteristic. Moreover, if only a limited number of defects is present their locations within the superlattice structure can directly be detected therefrom. Our simulations show that due to the expansion of the high-field domain with increasing voltage the domain boundary effectively "scans" the superlattice well by well.

Special attention is devoted to doping fluctuations. A bifurcation analysis explains how the current-voltage characteristic changes with increasing disorder as a result of a shift of the instability points and stabilization of hitherto unstable (and thus not observable) branches. Simple analytic considerations show that in the absence of other types of disorder the degree of doping fluctuations can be directly read off from the characteristic.

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Electron channel with high carrier mobility at the interface of isotype II broken-gap p-GaInAsSb/p-InAs single heterojuctions

M.P.Mikhailova, T.I.Voronina, T.S.Lagunova, K.D.Moiseev,

S.A.Obukhov, A.E.Rozov and Yu.P.Yakovlev

Ioffe Physical Technical Institute, RAS, St.Petersburg, 194021, Russia

We report the first observation of electron channel with high carrier mobility (u_H=50,000-70,000 cm^2/Vs) at the interface of isotype II p-GaInAsSb/p-InAs single heterojuctions with a broken-gap alignment. Weak temperature and doping level dependence of Hall mobility in the range 4.2-200K was obtained. It was an evidence that predominant carrier scattering mechanism is interface roughness. Strong Shubnikov-de Haas oscillations and anisotropy of longitudinal magnetoresistance were found in the p-p samples with various doping level of quaternary layers at T=1.5-10K and moderate magnetic field (up to B=5T). Some important parameters were evaluated from these experiments. Effective mass $m^*=0.026m_0$ equal to electron mass in InAs was found. It confirms a location of the electron channel at the InAs-side. 2D-electron concentration in the channel was $n_s \sim 3*10^{11}$ cm^{-2}, Dingle temperature (T_D) was equal to 1.7 meV and 5.0 meV at 1.5K and 4.2K respectively. Momentum relaxation time $\tau=1.5*10^{-12}$ s deduced from broadering parameter of Landau level was in a good agreement with a value found from Hall mobility measuring. Existence of electron channel at the interface was demonstrated also by scanning tunnel microscopy (STM) studing of cleavage of the p-GaInAsSb/p-InA structure in air at room temperature.

Obtained results demonstrated high quality unterface of GaInAsSb/InAs heterostructures grown by LPE on InAs substrate. Such heterostructures are very promising for creation of mid-infrared optoelectronic devices. This work was supported in part by Russian Fundamental Sciences Foundation grant N96-02 117841a.

LIGHT-HOLE RESONANT TUNNELING THROUGH TENSILE-STRAINED GaInAs QUANTUM WELLS

J.F. Lampin, X. Wallart, J.P. Gouy and F. Mollot

Institut d'Electronique et de microélectronique du Nord, Villeneuve d'ascq, France
U.M.R. C.N.R.S. 9929

Hole based devices always have poor performances compared with electron based devices, so, improving hole transport is a crucial challenge. Hole transport is limited by the low mobility, due to the preponderance of heavy-holes (HH). To enhance the light-holes (LH), the only solution is to use a strain which splits the valence band, in such a manner that the LH band becomes the fundamental one. As we are concerned in the present work by vertical LH transport, we need a tensile strain. Such a strain can be obtained on InP substrates in $In_xGa_{1-x}As$ layers for $x < 0.53$. Obviously, a large splitting is obtained for a large strain, but the critical thickness for relaxation drastically decreases. LH-HH splitting larger than kT at room temperature need mismatches larger than 1 %, leading to critical thicknesses in order of 10 nm. So, quantum confinement effect has to be taken into account. It reduces the LH-HH splitting because LH are less confined than HH. However, it has been possible to design, grow and study LH resonant tunneling diodes (RTD), acting as 'light-hole filters'.

We first studied strained quantum wells (QW) embedded in lattice matched InAlAs or InP barriers. These structures were grown by gas source molecular-beam epitaxy (GSMBE). Different thicknesses and mismatches (from 0 to 1.6 %) of the GaInAs layer were realized. Structural analysis had been done by high-resolution X-ray diffraction. Photoluminescence and photocurrent excitation were used in order to determine the LH-HH splitting as large as 50 meV for a 1% misfit. A fundamental LH towards HH transition was observed when the QW thickness decreases. Calculations of valence band energy levels have been done with deformation potentials in the frame of the Kane formalism.

Finally, we realized and characterized p-i-p RTD. Hole resonances were observed at low temperature. A lattice-matched QW was compared to and a tensile-strained one. At present time, the LH resonance of the strained RTD is not enhanced. As far as we know, this is the first report of resonant tunneling of holes in the InP system.

Probing nonparabolic conduction subbands in nanoscale InGaAs/InAlAs quantum wells with cyclotron resonance in very high magnetic fields

N. Kotera[a], Y. Shimamoto[b], H. Arimoto[b], K. Tanaka[a], T. Mishima[c] and N. Miura[b]

[a]Kyushu Institute of Technology, Iizuka, Fukuoka 820, Japan [b]ISSP, University of Tokyo, Roppongi, Minato-ku 106, Japan [c]Central Research Laboratory, Hitachi Ltd., Kokubunji, Tokyo 185, Japan

Nonparabolicity of the conduction subbands within quantum wells of the narrow-bandgap semiconductor is enhanced especially in nanoscale potential wells. In this paper, the effective masses of conduction subband in a direction parallel to the well plane have been clarified using 5-nm-wide wells of $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ hundred-multi-quantum well structures. Specimens were modulation-doped for cyclotron experiments. In the first place, two conduction subbands within the 0.5-eV-deep InGaAs well were clearly observed in 1.5-μm-band interband optical transmission spectra. The transition energies [1] were 0.865 and 1.182 eV. In the second place, the mass depending on the energy in the ground conduction subband was determined with 119-μm and 10.6-μm infrared transmission under magnetic fields up to 100 Tesla. The effective mass was $0.061m_0$ at 40 meV above the subband edge. The effective mass at 176 meV was deduced to be $0.064m_0$. The masses were larger than the polaron mass [2] and 50%-higher than the bulk band-edge mass of $0.041m_0$.

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Transport of Hot Electrons in Quasi-Continuum Above Multi Quantum-Well Structures

S. Maimon, E. Finkman, G. Bahir, and S. E. Schacham*

Dept. of Electrical Engineering and Solid State Institute, Technion Israel Institute of Technology Technion City, Haifa 32000, ISRAEL

**Dept. of Electrical and Electronic Engineering, College of Judea and Samaria, Ariel, ISRAEL*

The mobility of optically excited carriers traveling perpendicular to the epitaxial layers in quantum well infrared photodetectors (QWIP) structures is investigated. The various scattering mechanisms affecting the mobility as a function of excitation energy are analyzed. One of the most interesting phenomena is that in multiple quantum wells (MQWs), the average energy of the optically excited carriers can be considerably larger than that of thermally excited carriers. This is due to the fact that while in bulk semiconductors thermalization time is orders of magnitude shorter than the lifetime, here the thermalization time is longer than the electron recapture time into the well. Therefore, thermalization is negligible, and unlike the situation in bulk semiconductors, the electrons remain hot through their transport process. The dominant scattering mechanism is due to unscreened ionized impurities in the barrier, for which the mobility increases with increased energy. Thus it is expected that as the excitation energy increases, the perpendicular mobility increases. This holds as long as the kinetic energy of the carriers above the barriers is smaller than that of longitudinal optical (LO) phonons $\hbar\omega_{LO}$. Once the kinetic energy reaches $\hbar\omega_{LO}$, an abrupt drop in the mobility should occur following the emission of a phonon. The process repeats itself for multiples of $\hbar\omega_{LO}$. This prediction was verified experimentally in InP/InGaAs MQW, proving that in MQW under low bias voltages, the average photocarriers energy is higher than thermal. Monte-Carlo simulations render excellent fit to measured data. A new model for the dominant unscreened ionized impurity scattering is presented, modifying Conwell-Weiskopf theory.

Design and modeling of PbTe wide quantum wells based on the n-i-p-i concept

G. Span, P. Ganitzer, G. Heigl, A. Homer, J. Oswald
Institute of Physics, University of Leoben, Franz Josef Str. 18, A-8700 Leoben, Austria
Fax: +43 3842 402 760, e-mail: span@unileoben.ac.at

Wide quantum wells (WQW) are of special interest because of their intermediate regime between 2D and 3D behaviour. In contrast to 2D-systems the confining potential in a WQW is strongly effected by the charge of the free carriers which does not allow a wide channel with a homogeneous electron density in a compositional heterostructure. The use of doping structures is much more suitable for realizing such a wide homogeneous channel. However, maintaining a sufficiently high carrier mobility without remote doping is not possible in most of the host semiconductors. PbTe is a well known exception which allows high mobilities ($>10^5$ $cm^2V^{-1}s^{-1}$) even in the presence of the dopants in the channel.

We present self consistent model calculations for PbTe wide and multiple quantum wells in a perpendicular magnetic field. According to the n-i-p-i concept, the design is based on a p-n-p structure with non-depleted n- and p-layers which form a wide quantum well (channel width 100 - 1000 nm). Into this well we insert additional thin p-layers in order to get potential barriers which "cut" the WQW into a multiple quantum well system. In this way also a new approach for the coupled bi-layer system is possible where in contrast to a GaAs/GaAlAs WQW the barrier potential can be tuned independently of the carrier density. A systematic study of the feedback of the carrier redistribution between the subband-Landau levels on the confining potential is performed and the resulting consequences for magneto transport experiments in the QHE regime are discussed. As an example, a result not expected from simple qualitative considerations is that the different potential minima of a non-periodic multiple quantum well are forced to match each other because of the carrier redistribution with increasing magnetic field. Another surprising result is that a WQW does not allow the occurrence of integer filling factor one. Starting with a WQW containing a homogeneous electron channel at zero magnetic field, it turns out that at magnetic fields where one gets close to filling factor one the potential switches self consistently to a weakly coupled multiple quantum well with individual filling factors already below one.

MILLIMETER-WAVE NEGATIVE DIFFERENTIAL CONDUCTANCE IN GaInAs/AlInAs SEMICONDUCTOR SUPERLATTICES

C. Minot, N. Sahri, H. Le Person, J.F. Palmier, J.C. Harmand and J.C. Esnault

FRANCE TELECOM, CNET/PAB, Laboratoire de Bagneux
196, avenue Henri Ravera, BP 107, 92225 Bagneux Cedex, FRANCE

It is now well established that static and low frequency non-linear conduction in semiconductor superlattices is adequately described by miniband transport as was first suggested by Esaki and Tsu. As a result, the frequency and noise limitations of microwave devices based on negative differential conductance are expected to be largely pushed upwards in superlattice oscillators, in comparison to the usual bulk material transferred electron devices.

In order to investigate the high frequency behavior of superlattice diodes, we have performed reflection gain measurements in the lower millimeter-wave range up to 65 GHz, in several GaInAs/(Ga,Al)InAs superlattices of moderately high miniband width (60-100 meV) and different barrier heights. The structures, of $n^+SR(n^-)n^+$ type ($n^-<1.5x10^{16}$ cm^{-3}), are processed in a small dimensions technology. They are designed to exhibit maximum gain above 30 GHz and avoid self-oscillation. A gain resonance behavior is actually observed beyond the critical fields between 30 and 65 GHz. It is explained owing to a simple admittance model in satisfactory agreement with the results obtained from the static characteristics. The voltage range of the gain is significantly reduced in the samples with lower barriers. This is discussed in terms of electron tunnelling into higher minibands and the continuum.

Temporal measurements have also been performed in two samples. They are mounted in a very wide band inverted-microstrip transmission line (cut-off frequency ~250 GHz), in which electro-optic sampling of electrical transients is achieved with picosecond resolution. The superlattice devices are driven by voltage steps or pulses, which are generated in ultrafast photoconductive gaps photoexcited by high repetition rate femtosecond light pulses. Above the critical voltage, the transmitted electrical transients are dominated by the natural oscillation of the superlattice structure, the frequency of which is approximately given by the inverse transit time and in accordance with the gain resonance frequency mentionned above, typically 50 GHz. In addition, the Fourier transforms of the responses clearly reveal higher order harmonics and demonstrate the generation capabilities of the superlattices at least up to 150 GHz. The spectrum is explained qualitatively by the small-signal admittance model. The negative differential conductance based on miniband transport thus persists in the superlattice over a broad frequency range, the extent of which is assessed on the basis of the momentum and energy relaxation times derived from numerical solutions of the Boltzmann equation.

NEGATIVE DIFFERENTIAL CONDUCTION IN BLOCH OSCILLATIONS REGIME IN HEXAGONAL SILICON CARBIDE POLYTYPES 4H, 6H AND 8H.

V.Sankin, I. Stolichnov

A.F.Ioffe Physico-Technical Institute, St. Petersburg, Russia

The paper is devoted to the experimental discovering of the Bloch oscillations effect connected with the Bragg reflection of electrons from the first miniband edge in superlattices of different silicon carbide polytypes. This phenomenon predicted by Esaky in 1970 is of high practical significance since it results in a negative differential conduction. In this study vertical electronic transport in natural superlattices of silicon carbide hexagonal polytypes was investigated in Bloch oscillations regime. The original experimental method was elaborated for this study to obtain in experimental structure the strong uniform electric field meeting the Bloch oscillations effect conditions and electronic current controlled independently on the electric field. Direct measurements have allowed to discover the negative differential conduction corresponding to Bloch oscillations for polytypes 4H, 6H and 8H, having superlattice constants 5Å, 7.5Å and 10 Å respectively. The most recent result is negative differential conduction for polytype 8H which is of special interest because it correlates well with the previously obtained data for 4H and 6H polytypes. In fact, the threshold electric fields for negative differential conduction arising for polytypes 4H, 6H and 8H are 290 kV/cm, 150 kV/cm and 110 kV/cm respectively. These data taking into account differences in the first miniband width which must be increased from 8H to 4H are in good agreement with criteria of the Bloch oscillation phenomenon. Thus according to the our analysis the negative differential conductance effects obtained were interpreted as a manifestation of the Bloch oscillations phenomenon.

VIRTUAL STATES, ABSOLUTE NEGATIVE CONDUCTIVITY AND MULTIPHOTON-ASSISTED TUNNELING IN SEMICONDUCTOR SUPERLATTICES

B.J. Keay,[a,*] S. Zeuner, C. Aversa, S.J. Allen Jr.,[a] J. Galán,[b] K.L.Campman,[c] K.D. Maranowski,[c] A.C. Gossard,[c] U.Bhattacharya,[d] M.J.W. Rodwell [d]

[a] Center for Free-electron Laser Studies, UCSB, Santa Barbara, CA 93106
[b] Ohio State University
[c] Materials Dept., UCSB, Santa Barbara, CA 93106
[d] ECE Dept., UCSB, Santa Barbara, CA 93106

Virtual processes[1,2] are an important part of quantum physics. In nonlinear optics, for example, virtual transitions explain such phenomena as harmonic generation and frequency mixing. They have also been incorporated into the Tien and Gordon[3] model of photon-assisted tunneling (PAT). This model has been used to describe PAT in the early work on superconducting diodes, as well as a host of other systems. According to the Tien and Gordon model it is expected that virtual states make contributions to the transport similar to that of the unperturbed energy levels. Furthermore, it has been shown that for weakly coupled quantum wells, and for high enough laser intensities, the PAT currents are dominated by purely virtual terms that are neglected in standard perturbative approaches.[4]

These remarkable predictions have received considerable experimental support in recent work at the Center for Free Electron Laser Studies. In particular, several new observations have been made using semiconductor superlattices bow-tie antenna coupled to intense terahertz electric fields. These observations include dynamic localization, absolute negative conductivity (ANC),[5] stimulated emission, multiphoton-assisted tunneling, photon-assisted tunneling induced electric field domains[6] and an oscillatory dependence of the induced current on laser power.

The observation of ANC and the oscillatory dependence of the induced current on laser power lends important support to the model of Tien and Gordon. The distinguishing prediction of their model is the Bessel function behavior of the PAT currents, where the argument of the Bessel functions is given by $\alpha = edE_{ac}/\hbar\omega$, and d is the superlattice period, E_{ac} is the laser field strength and $\hbar\omega$ is the photon energy. PAT currents that bare remarkable similarities to Bessel functions have been observed in both the emission and absorption channels.

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OBSERVATION OF SEQUENTIAL EXCITED-TO-EXCITED STATES RESONANT TUNNELING IN WEAKLY COUPLED SUPERLATTICES WITH WIDE QUANTUM WELLS

Yu.A.Efimov, Yu.A.Mityagin, V.N.Murzin, G.K.Rasulova

P.N.Lebedev Physical Institute, Leninsky pr., 53, 117924, Moscow, Russia

In present work the sequential excited-to-excited state resonant tunneling effect was observed for the first time in weakly coupled long period superlattices (SL) resulting in additional negative differential conductivity (NDC) resonances in multistable current-voltage characteristics. The results obtained show the evidence of the highly nonequilibrium distribution of carriers over subbands with energies below the optical phonon energy in SL under electric fields corresponding to high-field domains formation. A new type of electric field domains due to resonant tunneling between excited subbands in adjacent wells was considered, and experimental evidencies of such a domain existance were given.

The results were obtained by vertical transport measurements carried out on long period low doped GaAs/AlGaAs SL ($d_w = 350A, d_b = 120$ A, N = 30, $N_d = 5 \cdot 10^{15} cm^{-3}$) with profound current hysteresis [1], that increases, as was shown, with the number of domain. The investigated SL's characterized by several electronic subbands in each quantum well (three of them below the optical phonon energy) revealed up to 6 kinds of domains (1→n, where n = 2,3,...,7) in (I-V) characteristics. A proper choice of SL parameters allowed to achieve a very large current hysteresis (the plateau current values differed more tham 2 times for sweep-up and sweep-down I-V curves for 1→5, 1→6, 1→7 type domains). A set of multiple stable current branches, arising from different locations of the domain boundary along the SL (up to N-1, N - the number of periods of SL) [2], was observed inside the hysteresis region.

A pronounced structure on this multiple branches some of it in the form of additional oscillatory-like plateaus inside the hysteresis region was found. We attributed it to the effect of resonant tunneling in SL between excited subbands in adjacent wells. The additional oscillatory-like plateaus observed inside the hysteresis regions can be explained by the formation of a new type of domains, corresponding to resonant tunnelung between excited n=2 and n=6,7 subbands. The results of numerical simulation of sequential resonant tunneling and electric field domain formation in SL on the basis of the developed microscopic model taking into account a finite population of excited subbands confirmed this conclusion. The model calculation of I-V characteristics of SL as well as electric field and space charge profiles were carried out showing the mechanism of this new type domain formation accompanied by appearing of the additional space charge domain boundary.

Comparing the results of model calculations with experimental data the effective temperature of the electronic subsystem under experimental conditions was estimated to be of about 100K, thus being in an agreement with the results of intersubband emission measurements [3].

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Microscopic Modeling of Field Domains in Superlattices

Andreas Wacker and Antti-Pekka Jauho
Mikroelektronik Centret, Danmarks Tekniske Universitet, DK-2800 Lyngby

Doped semiconductor superlattices exhibit complicated current-voltage characteristics consisting of several branches (reflecting the number of wells) due to the formation of electric field domains (see, e.g., [1]). Within the domains the electric field as well as the carrier density are almost constant. Thus the current density is determined by intrinsic features of the superlattice. This is a much simpler situation compared to other semiconductor structures, such as the double-barrier resonant-tunneling diode, where the contacts strongly influence the field profile and the current densities by carrier injection.

We have calculated the tunneling current between the wells n and $n+1$ (which are only weakly coupled in most experiments) based on the following formula [2]:

$$I = 2e \sum_{\underline{p},\underline{k}} |T^{n+1,n}_{\underline{k},\underline{p}}|^2 \int_{-\infty}^{\infty} \frac{d\mathcal{E}}{2\pi\hbar} A_n(\underline{p},\mathcal{E}) A_{n+1}(\underline{k},\mathcal{E}+\epsilon F d)\,(n_F(\mathcal{E}) - n_F(\mathcal{E}+\epsilon F d))$$

To determine the couplings T and the spectral functions $A(k,\mathcal{E})$ the results of the Kronig-Penney model, as well as ionized impurity scattering, optical phonon scattering and surface roughness, are taken into account. Thus we can evaluate the current without any adjustable parameters. For sample 4 of [1] we obtain heights of 52μA and 0.7mA for the first and the second maximum, respectively, without interfacial roughness. The missing current of 20% (40% for the second maximum) may be explained by interfacial roughness, whose amount is not known. An investigation of various superlattices exhibits that the current depends very strongly both on the actual barrier thicknesses and on the surface roughness.

The N-shaped local current-field relation is the reason for the formation of field domains for large doping as well as for self-generated oscillations at lower doping, which has been shown on the basis of a rather simple model [3] or a fitted relation [4]. We compare these results with our microscopic calculation.

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GENERATION OF TERAHERTZ ELECTROMAGNETIC PULSES BY ELECTRICALLY HEATED ELECTRONS IN TWO-DIMENSIONAL SEMICONDUCTOR SYSTEMS

W. Xu, C. Zhang and S.M. Stewart
Department of Physics, University of Wollongong, NSW 2522, Australia

Optical generation of terahertz (THz) electromagnetic radiations has been studied rather extensively in recent years. In some practical device applications, it is desirable to be able to generate *electrically* the THz electromagnetic pulses. One of the mechanisms proposed is based on hot-electron electromagnetic emission through heating the electrons by pulsed electric fields. Recent experimental results have indicated that in AlGaAs/GaAs-based two-dimensional electron systems (2DESs), hot-electrons can play a very important role in generating THz electromagnetic radiations through, e.g., blackbody radiation[1] and hot-plasmon emission[2].

In this paper, we present a detailed theoretical study that looks into the effects of hot-electron interacting with LO-phonons on the blackbody radiations from AlGaAs-GaAs-AlGaAs quantum well structures. We have developed a model from which the intensity of electromagnetic radiation by heated electrons in a 2DES can be calculated as a function of photon frequency ω and electron temperature T_e, where the blackbody radiations are generated via electronic transitions accompanied by electron–LO-phonon interactions. The effect of the depletion of the electronic states, due to the fact that in the presence of THz electromagneitc radiations the inverse of the relaxation time for excited electrons is on the scale of the radiation frequency, is included by using the Breit-Wigner distribution of energy. The main results obtained from the present study are: 1) in a 2DES, THz radiations are mainly generated via inter-subband electronic transition channels; 2) the polarization of THz electromagnetic waves generated is along the growth direction; 3) the intensity of THz electromagnetic radiation increases rapidly with increasing electron temperature. When $T_e > 40$ K, a peak in the radiation generation can be observed around $\omega = |\varepsilon_n - \varepsilon_m|/\hbar$ with ε_n the electronic subband energy; 4) at a fixed electron temperature ($T_e > 40$ K), the strongest radiation is generated when the condition of electro-phonon resonance (i.e., $|\varepsilon_n - \varepsilon_{n'}| = \hbar\omega_{LO}$ with $\hbar\omega_{LO}$ the LO-phonon energy) is satisfied; 5) for an AlGaAs-GaAs-AlGaAs well system, the frequency of the THz radiation generated can be tuned by varying the width of the well layer; 6) the background radiation increases with increasing electron density; and 7) when $T_e > 40$ K, varying the lattice temperature only affects the electromagnetic generations in low-frequency regime.

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Thermoelectric Transport Properties of $Si/Si_{1-x}Ge_x/Si$ Two Dimensional Hole Gases

I.G. Gerleman, O.A. Mironov, P.J. Phillips, E.H.C. Parker and T.E Whall

Department of Physics, University of Warwick, Coventry, CV4 7AL, U.K.

The thermoelectric properties of $Si/Si_{1-x}Ge_x$ heterostructures are presented for the first time. Samples with two dimensional hole gases (2DHG's) of sheet carrier density 0.8 to 15×10^{11} cm^{-2}, Germanium content, x = 0.07 to 0.3 and hole mobilities between 970 and 11 100 cm^2/Vs have been measured between 2.5 K and room temperature. Interest in these measurements lies in two temperature regions.

In the temperature range 2.5 to 65 K, the dominance of phonon-drag on the thermopower is established, the behaviour of this system showing significant similarities in nature to that of the 2DEG's studied in other material systems[1]. The measured thermal conductivity and thermoelectric power are used to determine the relaxation time for the hole-phonon interaction and an established theoretical model is used to extract new information regarding the deformation potentials for acoustic phonon scattering and interface roughness scattering in the strained SiGe alloy layer.

From 65K to room temperature, information regarding the energy dependence for hole scattering due to various mechanisms has been found via study of the prevailing diffusion thermopower at these temperatures. These measurements promise new information regarding the relevant mobility limiting scattering mechanisms for room temperature device operation.

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Acoustoconductivity of quantum wires

A. Shik
A.F.Ioffe Physical-Technical Institute, 194021 St-Petersburg, Russia;
M. Blencowe
Blackett Laboratory, Imperial College of Science, Technology and Medicine, London SW7 2BZ, UK

The change of conductivity in quantum wires under the influence of non-equilibrium phonons is considered theoretically. The particular mechanism of this acoustoconductivity (AC) is different for different wire lengths L. For long wires with L exceeding the localization length, the main effect is connected with the phonon-induced partial delocalization of carriers. In this case AC will be positive. The quantitative theory of the phenomenon is based on Anderson's scaling expression for a one-dimensional conductivity and is reminiscent of the temperature dependence of the conductivity of thin wires investigated in [1]. The probability of electron-phonon interaction and, hence, the amplitude of AC oscillates with the electron density in a wire, having maxima when the Fermi level E_F coincides with the edge of some one-dimensional subband. All these regularities are in agreement with the recent experimental data [2]. Details of the AC vs E_F curve depend on the distribution function of non-equilibrium phonons which, in turn, is determined by the method of phonon generation and geometry of the experiment. For short, ballistic wires, non-equilibrium phonons cause additional backscattering of carriers and AC must be negative.

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INFRARED INDUCED EMISSION FROM SILICON QUANTUM WIRES

N.T.Bagraev* , E.I.Chaikina* , W.Gehlhoff** , L.E.Klyachkin*, I.I.Markov*

*A.F.Ioffe Physico-Technical Institute, St.Petersburg, 194021, Russia

**Technische Universität Berlin, Arbeitsgruppe EPR am Institut für Festkörperphysik, Rudower Chaussee 5, D-12484 Berlin, Germany

We present the first findings of the infrared induced emission from the silicon quantum wires, which is due to the formation of a correlation gap in the DOS of degenerate hole gas. The quantum wires of this kind are created by electrostatic confining potential inside ultra-shallow p^+-n junctions which are realized using controlled surface injection of self-interstitials and vacancies in the process of non-equilibrium boron diffusion.

The diffusion experiments involving boron were performed from gas phase into 350 μm thick n-type Si (100) wafers. Diffusion profiles measured using SIMS technique demonstrate the depths in the range from 5 nm to 20 nm. The cyclotron resonance findings show that the p^+ diffusion profiles consist of both natural longitudinal and lateral quantum wells. Besides, the crystallographically dependent quantized conductance obtained at high temperature (77 K and 300 K) has revealed the quantum wires induced inside natural quantum wells by strong electrostatic confining potential. Temperature dependencies of thermal friction coefficient demonstrate the formation of a correlation gap in the DOS of degenerate hole gas in the crystallographically oriented quantum wires.

The generation of similar quantum wires with isolated quantum dots using external electric fields has been found to be responsible for the infrared emission in the range 1 - 10 μm, which is induced by the injection of non-equilibrium carriers into quantum wire systems. The threshold character of the irradiative power and dynamic spectrum narrowing found at 3591 nm, 3744 nm, 3969 nm, 4457 nm and 4881 nm as a function of the current that traverses the quantum wire with isolated quantum dots are evidence of light stimulated emission from silicon nanostructures.

Acoustic phonon modes of free-standing rectangular wires

N. Nishiguchi[†], Y. Ando[†], and M. N. Wybourne[††]
Department of Applied Physics, Hokkaido University, Sapporo 060, Japan[†]
Department of Physics, University of Oregon, Eugene, Oregon 97403, USA[††]

Energy loss from hot electrons in nanostructures is expected to be influenced by the optical and acoustic phonon spectrum of the structure. The spectrum will be modified when the phase coherence length of the phonons approaches the physical dimensions of the sample. In this paper we discuss the near zone center acoustic phonon spectrum of quasi-one dimensional rectangular wires of cubic crystals. We apply a resonant ultrasonic method[1] to calculate and investigate the mode structure. The normal modes are classified according to their spatial symmetries into one compressional mode termed the dilatational mode and two kinds of non-compressional modes referred to as the torsional and flexural modes. Dispersion relations of these modes are obtained for square wires with cross sectional dimensions 100Å×100Å, taking account of anisotropic elasticity of constituent materials. They show several phonon subbands below 0.5THz. Dependence of the dispersion relations on cross sectional aspect ratio is investigated, and the dispersion relations for a flat rectangular wire are compared with those of the approximate hybrid modes referred to as the thickness and width modes.[2] Examining the displacement vectors, we found that the lowest subbands of the normal modes are acoustic edge modes.

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Highly Confined T-shaped Quantum Wires

H. Gislason, W. Langbein, and J.M.Hvam

Mikroelektronik Centret, The Technical University of Denmark, bldg. 345e, DK-2800 Lyngby, Denmark

The best reported one-dimensional confinement energies, for quantum wires formed at the T-shaped intersections between multiple quantum wells (MQWs) grown on (001) oriented GaAs substrates, and a (110) oriented quantum well (QW) overgrown on the cleaved edge, are below 30 meV.[1] We demonstrate confinement energies in excess of 50 meV. This is achieved by an optimized design of the QW widths and the aluminum contents incorporated in the structure. The design is derived from a theoretical calculation of the confined electronic states using an effective mass approach for the conduction band states and a six-band **k·p** calculation for the valence band states. In the optimized design, the (001) and (110) QWs have equal ground state energies for the heavy-hole exciton. To match these energies, the transition energy of the (001) MQW is measured after growth, and the transition energy of the overgrown (110) QW is designed to coinside with this energy. This procedure is especially important for MQWs with aluminum in the wells, giving rise to deviations from the expected transition energy. For the overgrowth, a high control of the (110) oriented GaAs/$Al_{0.3}Ga_{0.7}As$ QWs is necessary. We investigate theoretically and experimentally 20 to 200 Å wide (110) oriented GaAs quantum wells grown on (110) oriented substrates and cleaved edges. Photoluminescence transition energies are found to be in good agreement with theory for all well widths. The mean well width is controllable to 1 monolayer accuracy and an effective well width fluctuation of 3.7 Å is derived from the photoluminescence linewidths.

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Fabrication and photoluminescence of AlGaAs/GaAs quantum wire superlattices on V-grooved substrate

Xue-Lun Wang[1)], Mutsuo Ogura[1)], Hirofumi Matsuhata[1)] and Tetsuya Tada[2),1)]
[1)]Electrotechnical Laboratory, 1-1-4 Umezono, Tsukuba 305, Japan
[2)]JRCAT, National Insitute for Advanced Interdisciplinary Research
1-1-4 Higashi, Tsukuba 305, Japan

We report some unique photoluminescence (PL) characteristics observed from AlGaAs/GaAs quantum wire superlattices (QWR-SL). The superlattice samples were grown on V-grooved substrates using flow rate modulation epitaxy (FME), a modified MOVPE growth technique, by which high growth selectivity could be achieved at low growth temperature (600°C) [1)]. Figure 1 shows the TEM image of a 20 period AlGaAs(80Å)/GaAs(45Å) superlattice. As can be seen from Fig.1, very uniform quantum wire array was formed, except for the first 2~3 periods.

Figure 2 shows the 12 K PL spectra of the superlattice sample and a 45Å thick single quantum wire (SQWR) sample. For PL measurement, parts of the structures surrounding the quantum wire active region were removed to enhance the carrier capture efficiency of the active region [2-3)]. In the spectrum of the SQWR sample, a single peak corresponding to the ground state recombination was observed. To the contrary, two side-peaks were observed in the QWR-SL spectrum, as indicated by arrows in Fig.2. These side-peaks were confirmed to result from intrinsic recombination by the temperature and excitation power dependence of the PL spectra, with the higher energy peak being most likely due to the n=2 subband transition. We also peformed time resolved (TR) PL to investigate mechanism for the appearance of the side-peaks. A very long life time was observed for the QWR-SL ground state peak as compaerd with the SQWR from the TR-PL spectra given in Fig.3. The reason for the long PL life time and its correlation to the side-peaks are under investigation.

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Fig.1 TEM image of QWR-SL

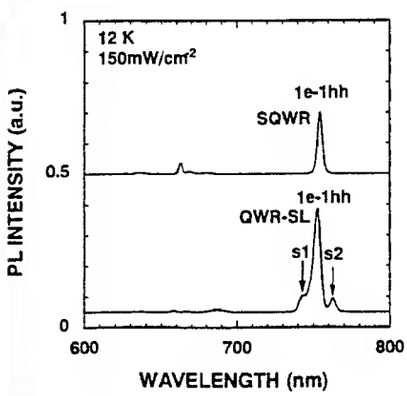


Fig.2 12 K PL spectra

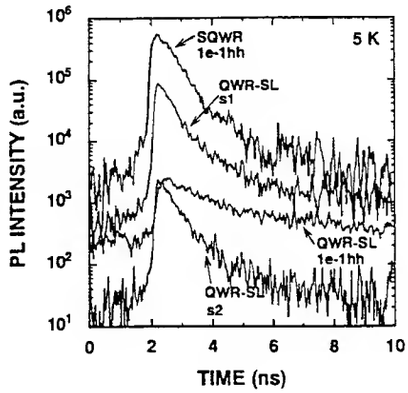


Fig.3 TR-PL spectra

Normal-Super-Normal Double Tunnel Junction Fabricated in a Split-Gate Wire

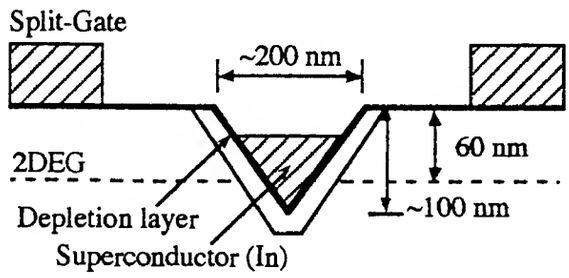
N. Aoki, T. Kikutani, A. Oki, C.U. Hong, H. Hori and S. Yamada

Japan Advanced Institute of Science and Technology (JAIST) - Hokuriku

By using scanning tunneling microscope (STM) lithography, we made a new microstructure which has a buried superconductor (indium) dot in the center of an usual split-gate quantum wire. In such a structure, if the wire is properly squeezed, the *In*-dot is linked via depletion layers to narrow two-dimensional electron gas (2DEG) regions located at 60 nm deep from the surface. Lower figure is a schematic cross-sectional view of our sample showing the formation of Normal-Super-Normal (NSN) double tunnel junction.

For STM lithography, we have employed a combined scanning electron microscope (SEM) / STM / atomic force microscope (AFM) system and carried out two-step fabrication process. In a first step, we approached a tungsten STM tip in a split-gate, and made a hole (almost a 200 nm diameter and a 100 nm depth pit-cone) by applying a single voltage pulse between a tip and a sample (GaAs). In a second step, indium coated STM tip or AFM cantilever was used to create a small *In*-dot in the hole by a field evaporation. The size of the split-gate wire which was fabricated by electron beam (EB) lithography and a Ti/Au lift-off technique, was typically 2 μm long and 1.2 μm wide. The 2DEG initially had a mobility of μ_e=1.7*10^5 cm^2/V·sec and a sheet electron density of n_s=4*10^{11} /cm^2 at 77 K.

We have measured basic transport properties of such a sample at 4.2 and 1.5 K because the superconducting critical temperature (T_c) of bulk *In* is 3.4 K. Especially in the experiment at 1.5 K, we observed following characteristic features in the DC-conductance against applied negative split-gate voltage (V_g): There have observed several conductance steps below $2e^2/h$ in the V_g range just before the pinch-off. After the pinch-off, small but highly periodic oscillations were observed. Although the origin of the behaviors are not completely clarified yet, a tight coupling between the *In*-dot and the 2DEG might play an important role. Such a coupling is possible because the coherence length of In (typically 300 nm) is probably larger than the thickness of the depletion layer (~100 nm).



Near Field Microscopy of Semiconductor Waveguides

C. D. Poweleit,[a] S. M. Lindsay,[a] D. H. Nagaski,[b] J. T. Boyd,[b] and H. E. Jackson[a]

[a] *Department of Physics, University of Cincinnati, Cincinnati, OH, 45220-0011, USA*

[b] *Department of Electrical and Computer Engineering, University of Cincinnati, Cincinnati, OH 45221-0030, USA*

The use of near field optical microscopy (NSOM) to probe electric field distributions in optical waveguides provides new insights into waveguides with subwavelength spatial resolution. We report NSOM measurements of the guided mode intensity distributions in AlGaAs heterostructure waveguide samples. Measurements of the modal variations in a multimode $Al_{0.24}Ga0_{0.76}As$ optical channel waveguide were carried out employing optical shear force feedback to maintain the fiber probe at a constant height above the waveguide surface (the evanescent field vertical decay length is ~20 nm,), while scanning transverse to the propagation direction. The results are compared with a beam propagation method analysis.

NSOM measurement of a *single mode* $Al_{0.24}Ga0_{0.76}As$ optical channel waveguide have been carried out transverse to the propagation direction. We extract from the observed cosine squared dependence of the intensity over the waveguide region the propagation constant k_y. Outside the waveguide structure, we measure the decay length z of the evanescent field parallel to the plane of the waveguide. The two waveguide constants determine the effective index of the regions both inside of and outside the structure. Finally, we observe an enhanced signal at the edges of the confinement regions of these semiconductor optical waveguides. We explore the origin of this enhancement and compare our experimental results with detailed model calculations carried out using the beam propagation method.

ELECTRO-OPTIC PROCESSES IN InGaAs/GaAs QUANTUM WIRES GROWN ON PATTERNED SUBSTRATES

R.Rinaldi, M.DeVittorio, and R.Cingolani

Dipartimento Scienza dei Materiali - Universita' di Lecce - 73100 Lecce, Italy

L.DeCaro, L.Tapfer

Centro Nazionale Ricerca e Sviluppo Materiali - 72100 Brindisi - Italy

U.Marti and F.K.Reinhart

Ecole Politechnique Federale de Lausanne, CH-1015 Lausanne - Switzerland

We have investigated the electro-optic properties of excitons confined in strained V-grooved InGaAs/GaAs quantum wires of lateral width below 20 nm. The assessment of the linear optical properties has been performed by means of photoluminescence excitation, providing clear evidence of high-quantum number transitions. The experimentally determined transition energies have been compared to the calculated confinement energies, taking into account the internal piezoelectric field originating from the off-diagonal components of the strain matrix which have to be considered for layers grown along the higher index surfaces. Such piezoelectric field is found to vary along the wire profile, reaching a maximum of about 20 kV/cm at the top of the quantum wire wings. This changes the lateral dependence of the offset value. The internal piezoelectric field is found to reduce the exciton binding energy of the exciton, which has been measured by magnetoluminesce experiments. The obtained value is about 50 % smaller than that expected for the planar quantum well grown on (100) from which the wire originates. Based on these experiments we have fabricated mesa structures including p-i-n diodes with InGaAs wires in the depletion ragion. A strong electric field dependence of the luminescence and photocurrent is observed as a function of the external polarization. The optical spectra reveal a strong red-shift and the suppression of the luminescence with increasing polarization. The observed quantum confined Stark effect (QCSE) exhibits an anomalous behavior, since both the red-shift and the non-linearity can be observed either under reverse or direct bias, though with different switching voltages. This peculiar behavior is ascribed to the vectorial composition of the internal piezoelectric field and of the external field resulting in a total polarization component which reduces the overlap of the carrier wavefunctions along the lateral confinement direction of the quantum wires. A theoretical modelling of this QCSE will be also presented.

Nonlinear Optical Properties of Semiconductor Quantum Wires.

V.Dneprovskii, N.Gushina, V.Karavanskii*, V.Poborchii, I.Salamatina**, and E.Zhukov**

Moscow St. University, Dept. of Physics, 119899 Moscow, Russia;
Fax:7−095−9393731; E−mail: dnepr@scond.phys.msu.su
*General Physics Institute, 117942 Moscow, Russia
**Ioffe Physico−Technical Institute, St.Petersburg 194021, Russia

Nonlinear optical transmission at discrete frequencies (bleaching bands) has been observed for the first time in GaAs and CdSe quantum wires (QWrs) crystallized in chrysotile asbestos nanotubes with average diameter ≈ 6 nm and in quantum wires and dots of CdS crystallized in the transparent molecular filter (mica with through empty channels). The induced decrease of absorption has been explained by filling of the size−quantized energy bands of QWrs with nonequilibrium carriers (saturation effect).

The existing methods of semiconductor QWrs manufacture in which MBE or MOCVD is used don't allow to get samples with appropriate volume and density of nanostructures for optical absorption and nonlinear optical absorption measurements. We have used the samples of two types: 1. cylindrical GaAs and CdSe QWrs have been crystallized in crysotile asbestos nanotubes with average diameter 6 nm that is comparable with the de Broglie wavelength of the electron; 2. a chemosorption layer by layer method has been utilized to create nanostructures of designed size by crystallizing semiconductor inside the empty channels of the transparent matrix. CdS has been crystallized in the channels of mica made by preliminary ion's bombardment using accelerator. The size of the channels and consequently of the nanostructures depends upon the type of the ions and their energy. Picosecond laser saturation spectroscopy (pump and probe) method [1] has been applied to investigate nonlinear optical properties of semiconductor QWrs.

Bleaching bands have been observed in differential transmission (DT) spectra of GaAs [2] and CdSe QWrs whose energy positions coincide with corresponding "hills" in the linear absorption (LA) spectra and with the

Excitonic Non-Linear Magneto-Optical Properties of a Quantum Wire

A. Balandin and S. Bandyopadhyay
Department of Electrical Engineering, University of Nebraska
Lincoln, Nebraska 68588, USA[1]

We have theoretically investigated the excitonic optical non-linearity in a quantum wire in the presence of a magnetic field using the rotating wave approximation. The non-linearity is caused by exciton-exciton interaction and the formation of excitonic molecules (biexcitons) [1,2]. This interaction is likely to be the dominant mechanism for optical non-linearity and the leading contribution to the third-order non-linear susceptibility $\chi^{(3)}$ in semiconductor quantum wires. The value of $\chi^{(3)}$ is enhanced manyfold in quantum wires because of one-dimensional confinement which increases the binding energies of all excitonic complexes.

We have calculated both the real and imaginary parts of $\chi^{(3)}$ in a quantum wire, arising from exciton-exciton interaction under optical pumping, as a function of an external magnetic field and pump-probe detuning frequencies. The imaginary part of $\chi^{(3)}$ exhibits a negative peak associated with the bleaching of the excitonic resonance and a positive, broad, off-resonance peak associated with biexciton formation. The amplitude, lineshape and spectral frequency of both peaks are quite sensitive to the magnetic field. This opens up the possibility of using a magnetic field to probe the mechanism underlying optical non-linearity in a quantum wire. Furthermore, the field can be used to *tune* the non-linear optical properties over a range of frequencies which has device applications (e.g. magnetically tuned couplers, limiters, mixers, phase-shifters, switches and magneto-optic logic).

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[1]On leave from the University of Notre Dame, Notre Dame, Indiana 46556, USA
[2]Supported by the U. S. Army Research Office under grant number DAAH04-95-1-0586

RAMAN SCATTERING FROM CONFINED PHONONS IN GaAs/AlGaAs QUANTUM WIRES

B. H. Bairamov[1,2], A. Aydinli[1], B. Tanatar[1], , F.N. Timofeev[1,2],

V. Smirnitski[1,2],S.V. Ivanov[2], B.Y.Mel'tser[2]

[1]*Department of Physics, Bilkent University, 06533, Ankara, Turkey*

[2]*A.F.Ioffe Physico-Technical Institute, Russian Academy of Sciences,*

26, St. Petersburg, 194021, Russian Federation

We report on photoluminescence and Raman scattering from GaAs/AlGaAs quantum wires prepared by molecular beam epitaxial growth of GaAs/AlGaAs quantum well, followed by holographic patterning, reactive ion etching, and anodic thinning. We propose to have found evidence for confined phonon modes in GaAs quantum wires which seem to agree well with the dispersive continuum theory of Enderlein [Phys. Rev. B47, 2162 (1993)] as applied to GaAs/AlGaAs systems. The observed good agreement between experimental value of longitudinal confined phonon modes at 285.6 cm^{-1} with that calculated in this model as well as the absence of TO(Γ) phonon mode in the spectra of all samples indicate high crystalline quality of the fabricated quantum wires using reactive ion etching and anodic oxidation techniques.

INTRODUCING SELF-CONSISTENCY TO EDGE STATE SCATTERING IN QUANTUM DOTS: EXPERIMENTAL IMPLICATIONS

JP Bird, M Stopa, K Ishibashi, Y Aoyagi, and T Sugano
Frontier Research Program, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-01, JAPAN

Application of a strong magnetic field dramatically modifies the self consistent charge distribution of a two dimensional electron gas system, causing its potential profile to develop a series of magnetically evolving terraces. Although considerable, the implications of this evolution for magneto-transport in mesoscopic devices have not been widely considered to date. In particular, inter edge state scattering in small quantum dots has attracted much attention, as a probe of the discrete electronic spectrum induced by the dot confining potential. Such experiments are typically analysed by assuming a magnetically invariant, parabolic form to the potential. While the advantage of this approach is that the resulting energy spectrum can be determined analytically, the formation of magnetic terraces in real devices will actually give rise to a very different spectrum. Correct analysis of experiments, performed with the intention of probing the discrete level structure of small dots, therefore requires a proper treatment of self consistent effects.

In this report, we demonstrate the observation of experimental features in the magneto-transport characteristics of sub-micron scale quantum dots, which can only be accounted for by consideration of their magnetically evolving potential profile. Possibly the most striking of these is a series of resonant like departures from quantisation of the magneto-resistance, understood to result from back-scattering singularities. The resonances occur when a magnetic terrace passes through the Fermi level, inducing a massive enhancement in the local density of states. While the singularities can correspond to a near complete reflection of the applied current, we emphasise that they cannot be reproduced on assuming a field independent device profile. Calculations of the magneto-conductance based on an evolving profile, however, are able to accurately account for the observed amplitude and field positions of the resonances. Another surprising effect involves the Aharonov-Bohm oscillations, associated with tunneling via confined edge states of the dot. While the period of these is typically consistent, with the addition of a single flux quantum to the area enclosed by an edge state, in some cases we observe a sudden period doubling of the oscillations, which occurs over a well defined range of field. We discuss this effect in terms of a competition of charge re-arrangement within the dot, by once again referring to the form of the self consistent magneto-spectrum.

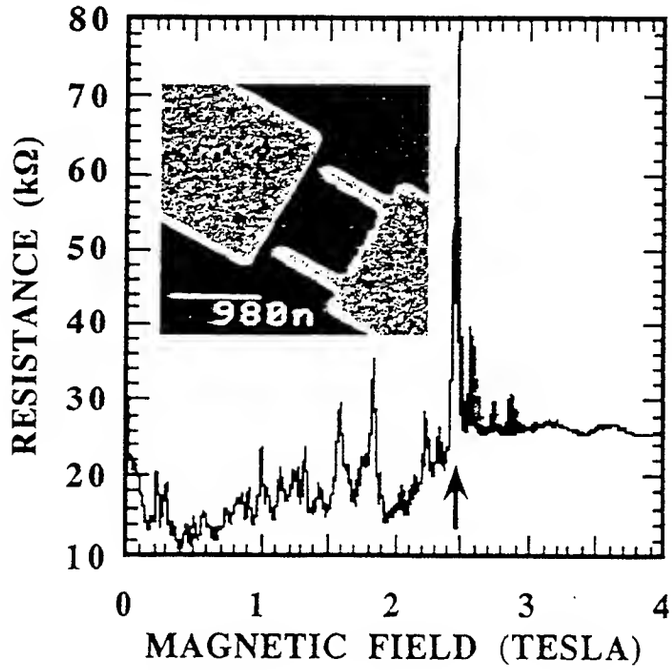

Figure: Low temperature magneto-resistance (10 mK) of a 0.4 μm dot shows a strong resonance at 2.5 T due to a magnetic terrace passing through the Fermi level. Inset: SEM micrograph of 1-μm dot, of similar design to the 0.4 μm dot. Space bar is roughly 1 μm.

MANY-ELECTRON GROUND STATES IN ANISOTROPIC PARABOLIC QUANTUM DOTS

A.Natori, M.Fujito, Y.Sugimoto and H.Yasunaga
Univ. of Electro-Communications, Chofu, Tokyo 182, Japan

The many-electron ground state in anisotropic parabolic quantum dots with the cylindrical symmetry are investigated, by means of an unrestricted Hartree-Fock method. The competition between the quantization energy and the electron-electron interaction is clarified. The effect of magnetic fields parallel to the cylindrical axis is also studied. The many-electron eigenstates can be assigned by two quantum numbers, L_z and S_z, the z-components of the total angular momentum and the total spin, respectively.

The spin state of the ground state changes from the ferromagnetic state to the paramagnetic state obeyed by the Hund rule, as the lateral size of a dot decreases. This is caused by competition between the exchange energy among electrons and the quantization energy of a confining potential. From the total energy of the ground state, the chemical potential and the differential capacitance of quantum dots are calculated as a function of electron number up to 30. The effect of the shell structure due to quantization appears clearly in electron number dependence of the chemical potential for a small dot, while it is smeared out by electron-electron interaction for a large dot. It also manifests in the capacitance, and the capacitance increases with characteristic oscillation related with the shell structure, by increasing the number of electrons. As the number N of electons increases, the calculated differential capacitance approaches the classical differential capacitance estimated from the average extent of the charge density of N-th electron.

With respect to the effect of the vertical extent of a dot, it appears more significantly, as the lateral size of a dot decreases. Especially on the capacitance of a small dot, the effect is enhanced at the special number of electrons, corresponding to the open shell structure of three electrons. In this special electron configuration, the many electron effect in a shell is enhanced. The strength of lateral confining potential increases in the magnetic field, and the effect of vertical extent appears remarkably in strong magnetic fields.

Temperature dependence of relaxation times in electron focusing and antidot structures made from $In_{0.53}Ga_{0.47}As/InP$ heterojunctions.

J. Heremans, General Motors Research and Development Center, Warren, MI, USA; V. Bayot, Unite PCPM, Universite Catholique de Louvain, Louvain-la-Neuve, Belgium; B.K. Fuller and C.M. Thrush, General Motors Research and Development Center, Warren, MI, USA.

The magnetoresistance of antidot lattices and the magnetic field dependence of the three-terminal resistance of transverse electron focusing (TEF) devices is studied in the 2-DEG in the lattice-matched $In_{0.53}Ga_{0.47}As/InP$ heterojunction system, as a function of temperature ($3\ K < T < 180\ K$). Ballistic effects are observed in both types of mesoscopic devices at temperatures exceeding 100 K, and are considerably more robust than Shubnikov - de Haas (SdH) oscillations. Two effects influence the decay in the amplitude of the magnetoresistance peaks in the antidot structures, and of the focusing peaks in the TEF devices: the thermal smearing of the Fermi surface, and the increase in the electron scattering time with increasing temperature due to the increase in electron-phonon scattering. The effect of thermal smearing can be modeled by convoluting the low-temperature peak shapes with Fermi statistics. This enables us to deduce the temperature dependencies of the scattering times for the different geometries, TEV and antidots devices. SdH data on similar samples are also available up to 30 K. Their temperature decay is dominated by thermal smearing of the Fermi surface, but values of the single-particle relaxation time can be obtained, though with limited accuracy. The temperature dependent part of these three relaxation times, focusing time, antidot relaxation time, and single-particle (SdH) relaxation time, will be compared in this talk. Electron-phonon influences the scattering times in different ways due to the influence of the scattering angle in the different geometries.

Single Electron Charging of the Quantum Dot: Beyond the Continuum Approximation

S. Nagaraja, P. Matagne, V. Y. Thean, J. P. Leburton
Beckman Institute for Advanced Science & Technology
University of Illinois, Urbana, IL 61801

Orthodox theories on single electron charging of quantum dots consider the states in the dot to form a quasi-continuum i.e. the seperation between the states $\Delta E < k_B T$ and $e^2/2C > k_B T$, where C is the capacitance of the dot (Likharev et al., 1986; Kastner et al.1991). Hence the energy needed to add an electron to the dot is just $e^2/2C$, to overcome the *coulomb blockade*.

In the present work we go beyond the quasi-continuum regime by imposing the condition of energy quantization in the dot. We solve the Schrödinger and Poisson equations self-consistently by discretizing the equations on a three-dimensional (3D) grid. The 3D Schrödinger equation is solved by the Iterative Extraction Orthogonalization Method (IEOM) (Kosloff & Tal-Ezer, 1986; Jovanovic & Leburton, 1994) which is very efficient when searching for a few eigenvalues. We report the resulting charging characteristics, variation of the electronic energy spectrum and the capacitance of a quantum dot conaining a few number of electrons. We also investigate the contribution of the *Exchange and Correlation* effects when included under the local density approximation (LDA).

The charging characteristics reflect the effect of quantization on the charging energy, and it is seen that the voltage steps are wider for N = 4, 8, 10 when the population of the dot (N) is even than when N is odd (Fig. 1). This is due to the additional energy required to lower the next unoccupied level on the Fermi level in order to add an additional electron in the dot already filled with an even number of spin degenerate electrons (Fig. 2). This effect for N = 6, is however swamped by a *coulomb degeneracy* when the levels 4 & 3 characterized by different wavefunction symmetries become almost degenerate because of coulomb bkockade in the dot. We also see

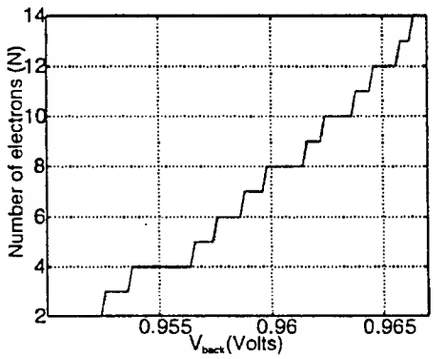

Fig. 1: Single Electron Charging at T = 0.25 K

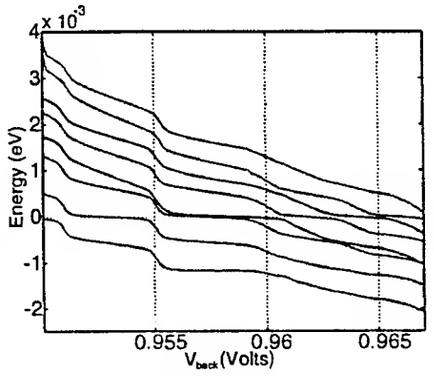

Fig. 2: Energy Spectrum Variation

that the change of symmetry between consecutive states also leads to an anti-crossing of levels between levels 3-4, 4-5, 5-6 and 6-7. We show that the gate capacitance of the dot varies for odd and even N electron occupation, and exhibits a general tendency to increase with N. The contribution of the Exchange and Correlation effects to the elecronic energy spectrum accounted for by the LDA appears to be weak. We believe that the weak influence of the LDA may be due to its limitation for a system with a few electrons in the dot

Coupled Quantum Dots as Quantum exclusive-OR Gate

José A. Brum and Pawel Hawrylak

Institute for Microstructural Sciences, National Research Council, Ottawa (Ont.), Canada, K1A OR6

A quantum exlcusive-OR gate (QXOR) is a fundamental building block of quantum circuits neccessary for the implementation of quantum computers. The QXOR can be realized with a 4-level system e.g 4 spins. We consider here a model of a QXOR device realizable with surface gate technology. The QXOR device consists of four coupled quantum dots, each dot in a corner of a square. Two of the dots are in contac with external leads. We consider small dots and assume a single orbital per dot. The dots are coupled with each other and with leads through a hopping matrix element. The effect of the magnetic field is included through Peierl's substitution. The four single particle states hybridize into an s-like, two p-like, and a d-like state. The magnetic field induces crossing of single particle energy levels. The QXOR device can be charged with up to N=8 electrons. We use exact diagonalization techniques in the configuration space to calculate physical properties of QXOR as a function of the number of electrons N and external perturbations in the form of electric and magnetic fields. This allows us to investigate the switching of the QXOR gate, and it's ability to store and transmit information. The effect of interactions is visible already in the two-electron system. A ground state of the QXOR device with N=2 electrons exhibits a singlet-triplet-singlet transition with increasing magnetic field. For larger number of electrons a rich spectrum of ground and excited states, classified by total spin and angular momentum, is obtained. These states determine the response of the device to external perturbations. We study how these perturbations can polarize the charge distribution in the device and how transport through QXOR can read this information.

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Field Dependent Phase Coherence of Trapped Electron in Gated Quantum Dot

Y.Ohkubo, N.Sasaki, Y.Ochiai, K.Ishibashi[1], J.P.Bird[1], Y.Aoyagi[1] and T.Sugano[1]

Department of Materials Science, Chiba University, 1-33Yayoi, Inage, Chiba, Chiba263, Japan
[1]Institute of Physical and Chemical Research, 2-1Hirosawa, Wako, Saitama351-01, Japan

We are studying quantum interference effects due to electron wave trapped in a gated quantum dot.[1)] We have observed conductance fluctuations (CF) in such ballistic structures fabricated in the high-mobility 2-dimensional electron gas (2DEG) of a GaAs/AlGaAs heterojunction using metallic gate method. Experimental results on the magnetic field dependence of the CF have enabled us to determine the importance of chaos behavior for the full understanding of interference effects of electron waves in ballistic quantum dot.

The gated dot structure was constructed on 2DEG GaAs/AlGaAs wafers, grown by molecular beam epitaxy, with a typical low temperature mobility, μ=20m^2/Vs and elastic mean free path, l_{mfp}=2.2 μm. The wafers were patterned into standard Hall bar configuration with a width of 80 μm and a voltage probe separation of 200 μm. Our gated quantum dot consists of one center gate and two point-contacts. The dot was formed by the center gate located between two narrow gates of the point-contact. Since the designed area of the dot was 0.8x0.8 μm^2, transport in the dot was expected to be in the ballistic regime.

The field dependence of the CF is discussed using a correlation field, ΔB_c, analysis since ΔB_c is found to increase at high magnetic fields. The phase breaking rate has been obtained from the slope of ΔB_c in a linear exponent of the field dependence.[2)] On the other hand, near zero fields, we have observed a negative magnetoresistance. Since the electron wave interference in our dot should not be determined from a weak localization mechanism as in diffusive samples, we can not apply such a localization process to negative magnetoresistance results. Also, we observed that the amplitude of the fluctuations δg at low magnetic fields is changed by the gate voltage of the entrance point-contact. The change suggests the relation between the channel number and the phase coherence in the dot. Here, we estimated the phase braking rate using theoretical calculation based on a chaotic transport picture in a quantum dot by considering a channel number of the phase braking channel in the dot.[3)] The result of magnetic field dependence shows that the phase braking rate at high fields becomes lower than that near zero field. We discuss this behavior in terms of a transition from chaotic to regular motion as well defined cyclotron orbits form in the dot.

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CONDITIONS FOR THE FUNCTIONALITY OF BASIC CELLS FOR QUANTUM CELLULAR AUTOMATA

M. Macucci and G. Iannaccone

Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Pisa,

Via Diotisalvi 2, I-56126 Pisa, Italy

A circuit based on the Quantum Cellular Automata scheme proposed by Lent, Tougaw, and Porod, basically consists of a crossword-like array of basic cells that interact with each other only by means of the capacitive coupling between adjacent cells. Each cell is made up of five quantum dots, four on the corners of a square and one in the center, and is occupied by only two electrons. Tunneling occurs between nearest neighbor and next-nearest neighbor dots, but not between different cells. Coulomb repulsion inside a single cell causes the electrons to occupy the dots on opposite corners, therefore there are two possible stable states, or "polarizations," which allow the storage of binary data. Configurations of such cells have been demonstrated which can be used to transmit information and to perform basic logic functions.

However, the fabrication of cells small enough as to contain only 2 electrons, and the realization of a control system for tuning the occupancy of each cell in the circuit, are clearly beyond the limits of semiconductor technology, at least in the mid-term future.

Therefore, the possibility of obtaining functional quantum cellular automata lies in our ability to design and fabricate basic cells containing few electrons (of the order of ten), which must be robust, in the sense that cell functionality is not compromised by small fluctuations in the number of electrons. However, for increasing number of electrons, intra-dot electron-electron repulsion tends to reduce cell polarization, and can inhibit cell functionality.

In this paper, we study the functionality of coupled basic cell structures containing few electrons (in the range 8-20) as a function of cell size, number of electrons, dielectric constant of the dot and barrier material. This objective is accomplished by solving self-consistently the 2D Schrödinger equation as a function of the quantities mentioned above, and of different polarization states enforced in one of the cells. The conditions for obtaining functional, bistable operation are finally assessed.

NONLINEAR LOW-TEMPERATURE TRANSPORT OF ELECTRONS THROUGH A MULTILEVEL QUANTUM DOT

T. Inoshita
Quantum Transition Project, JRDC
4-7-6-4F Komaba, Meguro-ku, Tokyo 153, Japan

Y. Kuramoto
Dept. of Physics, Tohoku Univ., Sendai 980, Japan

H. Sakaki
RCAST, Univ. of Tokyo, 4-6-1 Komaba, Tokyo 153, Japan

Intradot Coulomb repulsion noticeably affects the low-temperature transport of electrons through a quantum dot by inducing Kondo-type correlation [1-3]. Although the Kondo temperature T_K estimated initially in a single-level model [2] was discouragingly low, we have recently pointed out that T_K can be enhanced by orders of magnitude in a semiconductor dot due to its multilevel structure, and that T_K on the order of 1 K is possible in a properly designed dot [4].

In the present work, we have theoretically investigated nonlinear conductance through a multilevel dot at arbitrary temperatures using the infinite U Anderson model. In order to discuss nonlinear transport through a dot, it is essential to fully take into account (1) the finite current through the dot (i.e. nonequilibrium effects) due to Fermi level difference $\Delta\mu$ between the two leads, and (2) the strong Coulomb repulsion. This was accomplished by combining the nonequilibrium (Keldysh) Green's function method and the non-crossing approximation [5].

The result clearly indicates that differential conductance as a function of $\Delta\mu$ ($=eV$ where V is bias voltage) displays side peaks on both sides of the Kondo peak. These peaks are somewhat broadened by the finite current but are still clearly visible. Their separation is equal to the dot level separation and is nearly independent of the dot-lead transfer energy. Therefore if one applies a gate voltage on the dot to shift its energy levels rigidly, these peaks should remain at the same positions. The observation of these side peaks should provide unmistakable evidence of Kondo correlation.

When the number of dot levels is increased, the local density of states of the dot is strongly enhanced (suppressed) above (below) the lower of the two Fermi levels. We discuss experimental relevance of this singular behavior of the density of states.

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EXCITONS AND MULTI-EXCITON COMPLEXES BOUND TO A 2-D HOLE LAYER AT A SILICON SURFACE: THE KONDO EFFECT, THE COULOMB BLOCKADE AND A NEGATIVE PHOTOCONDUCTIVITY

P.D.Altukhov, E.G.Kuzminov, and G.V.Ivanov

A.F.Ioffe Physical-Technical Institute, Politekhnicheskaya st.26, 194021 St.-Petersburg, Russia

Recombination radiation line (S-Line) of 2-D holes and 2-D nonequilibrium electrons, bound to the [100] 2-D hole layer by the hole polarization attraction, is observed in luminescence spectra of silicon MOS structures. At the 2-D hole density $n_S<8\cdot10^{11}$ cm^{-2} and low surface electron-hole pair density n_P surface pairs exist as excitons [1] and biexcitons due to weak screening and weak k-space occupation. The circular polarization of the S-line in a transverse magnetic field is defined by the average electron spin. The average hole spin of the excitons is very small due to high Kondo temperature of the exciton and 2-D holes. The Kondo hole spin singlet of the exciton and 2-D holes is assumed to exist. The luminescence of biexcitons at low energy part of the S-line is not polarized in the magnetic field.

Luminescence line of multi-exciton complexes, bound to the 2-D hole layer, with number of excitons ~(2÷30) arises at low energy side of the S-line with increasing n_P. The average hole spin of the complexes in the magnetic field is small presumably due to Kondo effect. The Coulomb blockade of the complexes excludes a direct contribution of the complexes to a surface photoconductivity. The Coulomb blockade results from Coulomb repulsion of an extra hole in a complex, when an energy level of an extra hole is higher than the hole Fermi level. So, the resonant tunneling of holes through the complexes is weak. A significant negative photoconductivity of the 2-D holes is observed at n_P ~$(1\div5)\cdot10^{11}$ cm^{-2}. The negative photoconductivity is suppressed by a magnetic field. The decrease of the 2-D hole conductivity under photoexcitation can be explained by the quantum interference effects in the presence of large number of randomly distributed complexes. The system of multi-exciton complexes represents a selforganized quantum dot system coupled with the sea of 2-D holes.

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EXCITONIC OPTICAL TRANSITIONS AS A PROBE OF SELF-ORGANIZED GROWTH OF ZnTe (CdTe) ISLANDS IN (001)-GROWN CdTe (ZnTe) QUANTUM WELLS.

V. Calvo, Q.X. Zhao[*], P. Lefebvre, J. Allègre, A. Bellabchara, H. Mathieu and N. Magnea[**]

Groupe d'Etude des Semiconducteurs - CNRS - Université Montpellier II. Case courrier 074, 34095 Montpellier cedex 5. France.

[*] : Max-Planck Institut - Stuttgart

[**] : C.E.A. Grenoble, Département de Recherche Fondamentale sur la Matière Condensée / SP2M. 17, avenue des Martyrs. 38054 Grenoble. France.

Integer and fractional monomolecular layers of ZnTe have been inserted in CdTe-(Cd,Zn)Te quantum wells in order to trap light-hole excitons and to confer them a type I character. This result of lattice-mismatch strains has been verified by low-temperature photoluminescence, reflectance and piezoreflectance measurements compared to variational calculations of excitonic transition energies.

In addition, the possibility of self-organized growth of strained ZnTe islands has been investigated. Optical spectra have been recorded from a quantum well where two half-monolayers of ZnTe have been grown in symmetrical positions, in order to use excitons as probes of a possible specific stacking of ZnTe islands. To do so, reference samples, *i.e.* the basic "empty" quantum well and others where one or two integer monolayers of ZnTe have been introduced, have been also grown and investigated. Comparisons of direct and modulated optical spectra from all samples provide very strong indication that two fractional ZnTe layers, separated by a few CdTe monolayers, tend to grow in an ordered way : successive ZnTe islands appear to avoid growing on top of each other and to adopt a staggered lineup.

This behavior is comparable to the self-organization of InAs islands in GaAs matrix (1), although ZnTe islands seem to repel each other, while InAs yields "columns" of dots. According to the theory developed for metallic precipitates (2), this can be explained by the hardness difference between the matrix and islands. If the material of the inserts is softer than that of the matrix, as for InAs in GaAs, an inter-plane attraction occurs between the islands. In the opposite case, as for ZnTe in CdTe, a repulsion is produced between the islands.

To complete this study, piezo-optical measurements on ZnTe-based samples embedding CdTe monomolecular inserts, which show very efficient green luminescence, are also presented. Indications are seen of the coherent growth of CdTe islands.

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Quantum confinement effects on the optical phonons of CdTe quantum dots

A. M. de Paula, L. C. Barbosa, C. H. B. Cruz, O. L. Alves*, J. A. Sanjurjo and C. L. Cesar

Instituto de Física, Universidade Estadual de Campinas, Caixa Postal 6165, 13083-970 Campinas SP, Brazil

**Instituto de Química, Universidade Estadual de Campinas, Caixa Postal 6154, 13083-970 Campinas SP, Brazil*

The quantum-confinement effects on the optical properties of semiconductor quantum dots in doped-glasses is the subject of much current research. The interest arises because of the great potential of these materials for optical device applications due to their nonlinear optical properties.

In this work we present Raman scattering results for CdTe nanocrystals which clearly show the confinement effects on the phonon spectra as a function of the quantum dot size. We observed optical phonon modes, surface phonons and some of their overtone combinations. We show that the surface phonon scattering intensity increases as the quantum dot size decreases. Our results also show a decrease on the electron-phonon coupling as the nanocrystal size is decreased. These confinement effects are observed by changing the laser excitation energy, and thus tuning to resonance with the optical transitions for quantum dots of different sizes within their broad size distribution in semiconductor doped glasses.

The glass samples were prepared by melting a glass host containing SiO_2, B_2O_3, Na_2O and ZnO mixed with CdO and metallic Te. The semiconductor nanocrystallites are produced by a subsequent heat treatment. We present results for a sample annealed at 580 °C for 25 min. The CdTe quantum dot mean-radius obtained from the first peak in the absorption spectra considering the quantum confinement energy given by a $\mathbf{k} \cdot \mathbf{p}$ model is 3.6 nm [1]. For this sample, the width of the quantum dot distribution estimated from the absorption spectrum is about 10%.

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TECHNOLOGICAL ASPECTS OF PREPARATION OF SEMIMAGNETIC SEMICONDUCTOR QUANTUM DOTS

S.V.Medynskiy, P.I.Nikitin*, A.I.Savchuk, I.D.Stolyarchuk

Dept.Phys.Electronics, State University, Chernivtsi,274012,Ukraine,

*** General Physics Institute, Moscow, 117942, Russia**

In the last decade semiconductor quantum dots in the form of microcrystals dispersed in transparent matrix have been extensively investigated. However, only recently interest have appeared to zero-dimensional systems on the base of semimagnetic semiconductors. In this new field of research main problems are associated with technology of fabrication of such structures. Successful preparation of semimagnetic $Cd_{1-x}Mn_xTe$ and $Cd_{1-x}Mn_xSe$ in SiO_2 glass matrix by means of rf magnetron sputtering was reported in [1,2]. In this work we present analysis of other technological methods for fabrication of $Cd_{1-x}Mn_xTe$, $Cd_{1-x}Mn_xSe$ and $Pb_{1-x}Mn_xI_2$ microcrystals embedded in dielectric matrix.

Three different techniques were used for fabrication of the samples of semimagnetic semiconductor microcrystals. In the first method microcrystals were grown by melting of the semiconductor-doped fine powder borosilicate glasses. In order to minimize oxidation of particles activated carbon powder was added into container. Further growth of semiconductor particles and narrowing of size distribution was achieved during heat treatment process. Zeolite matrix have served as suspendid media for incorporating of nanoparticles in the second method. For example, the $Cd_{1-x}Mn_xSe$ crystallites were incorporated into supercages of zeolite by the vapor phase transport at 700° C for 40 hours. The third technique have consisted in embedding of $Pb_{1-x}Mn_xI_2$ microcrystals into polymer matrices. The obtained microcrystals were platelet-like in the shape because of layered structure of initial bulk crystals.

Stability of the prepared samples of $Cd_{1-x}Mn_xTe$ and $Cd_{1-x}Mn_xSe$ microcrystals at ambient conditions was good. However, the changes in optical properties of $Pb_{1-x}Mn_xI_2$ microcrystals were observed after irradiation with power visible light.

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GROUND-STATE ENERGY OF AN EXCITON IN A QUANTUM-DOT SUPERLATTICE GROWN ON A TERRACED SUBSTRATE

Guy Lamouche and Yves Lépine

Département de Physique et Groupe de Recherche en Physique et Technologie des Couches Minces

Université de Montréal, C.P. 6128, Succursale Centre-Ville, Montréal, Québec, Canada, H3C 3J7

For adequate material combinations, the growth of a fractional monolayer on a terraced substrate is expected to form a two-dimensional superlattice of flat square quantum boxes. Such InAs/GaAs[1] and InAs/InP[2] structures have already been reported. The optical characterization of the InAs/InP quantum-dot superlattices[3] clearly shows that, for a given superlattice period, the exciton binding energy decreases when the lateral dimension of the quantum dots decreases. In this work, we present a simple variational calculation of the ground-state energy of an exciton in such a structure. The treatment is performed within a two-band effective mass approximation. The variational wave function is based on the one-particle Bloch states related the extrema of the superlattice minibands and it allows Coulomb correlation in the superlattice plane. Numerical results are presented for the heavy-hole exciton in an InAs/InP quantum-dot superlattice. We give the exciton binding energy, the contribution of the electron-hole interaction to this energy, and the extension of the exciton wave function in the superlattice plane. Calculations are performed for the structures studied in Ref. 3 and a good agreement is found with experiment. Further calculations for other structures are provided to give a better picture of the effect of the superlattice parameters on the various contributions to the binding energy of the exciton.

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Size, Position and Direction Control on GaAs and InAs Nanowhisker Growth

T. Shimada, K. Hiruma, M. Shirai, M. Yazawa, K. Haraguchi,
M. Matsui and T. Katsuyama
Central Research Laboratory, Hitachi Ltd., Kokubunji, Tokyo 185, Japan
Tel:+81-423-23-1111, Fax:+81-423-27-7735, (Oral)

The self-organized and parallel growth of GaAs and InAs nanowhiskers is one of the most interesting methods to realize the high yield fabrication of nanometer-size devices. In this paper, control of size, position and direction on the GaAs and InAs nanowhisker growth is realized by a MOCVD method and the growth mechanism of the nanowhiskers is revealed by the SEM, TEM and photoluminescence observations.

(1) Size control, p/n doping and heterostructure formation

The diameter of the whisker can be controlled artificially, and even doping and composition control is possible along the length direction of the whisker[1]. The transition regions of p/n and heterostructure interfaces are as small as less than 5 nm.

(2) Positioning

We have succeeded in the artificial control of the growth position of the whisker[2]. The important point is the Au/Ga(In)As-alloy cluster positioning on the substrate before whisker growth. We found that the Au/Ga(In)As-alloy clusters are stably situated on the substrate during the MOCVD growth. In contrast to this, the Au clusters easily move on the substrate during the growth.

(3) Planar growth

The planar whiskers have advantages for the post processing such as patterning of the device and electrode formation on the whiskers, over those grown perpendicular to the surface. The essential points of planar growth technique is that; (a) the [111]B direction is parallel to the substrate surface and normal to the patterned side edges, and (b) how to situate Au-alloy dots on the suitable positions on the surfaces at the side walls. The positioned planar nanowhiskers are successfully grown by this method.

(4) Growth mechanism of the nanowhiskers

The growth direction of these whiskers is only [111]B which corresponds to the <111>As dangling bond direction. We have found that Au-alloy micro clusters play an important role in the growth of the whiskers[3]. Recently, growth mechanism has been clearly verified by using a transmission electron microscopy. An alloy cluster with the composition of Au : Ga : As = 72 : 23 : 5 can be observed on the top end of the whisker crystal in the case of the GaAs whisker growth. The whisker growth process is governed by the vapor-liquid-solid (VLS) growth mechanism.

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VERTICALLY COUPLED (IN,GA)AS QUANTUM DOTS IN A GAAS MATRIX.

A.O. Kosogov[1,2,3], P.Werner[1], N.N. Ledentsov[2,3], V.M. Ustinov[2], I.V.Kochnev[2], M.V.Maximov[2], N.A.Bert[2], P.S.Kop'ev[2], U.Gösele[1], D. Bimberg[3]

[1]Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, 06120 Halle, Germany

[2]A.F. Ioffe Physical-Technical Institute, 194021 St. Petersburg, Russia

[3]Technische Universität Berlin, Hardenbergstrasse 36, 10623 Berlin, Germany

The self-assembly of quantum structures promises to provide a mechanism for producing 3-D arrays of quantum dots (QD's) having potential applications in basic studies of quantum confinement as well as photonic devices. In this work structural and optical properties of (In,Ga)As vertically coupled dots (VECOD's) grown on GaAs (001) by MBE and MOCVD were investigated.

The VECOD's were formed by introducing of **N** (up to 10) cycles of 1.8 ML InAs or 2.5 ML $In_{0.5}Ga_{0.5}As$ deposition separated by 1.5-5 nm thick GaAs spacers. Electron microscopy (TEM) investigations showed that despite the difference in the islanding tendencies (QD size, density and shape) for InAs and $In_{0.5}Ga_{0.5}As$ [1] and regardless the growth technique, the resulting structures were composed of vertically aligned parts of (In,Ga)As separated by a few ML-thick GaAs regions. MBE grown InAs QD's with square shaped base were locally ordered along [100] and [010] directions. The QD's formed by $In_{0.5}Ga_{0.5}As$ deposition exhibited the circular or elongated along the [1-10] direction base shape, in this case the main directions of ordering were <100> and <110>. The lateral size and volume of (In,Ga)As islands progressively increased with each deposition cycle. Being more significant for $In_{0.5}Ga_{0.5}As$ QD's these changes decreased with increasing of GaAs spacer thickness and can be attributed to the locally reduced misfit above buried islands as well as to the vertical transfer of InAs from the buried to uncovered part of VECOD's during their growth.

For all samples investigated a good correlation between TEM data and photoluminescence (PL) spectra has been found. The PL intensity maximum was strongly shifted towards smaller photon energies in comparison with the energy expected for the uniform (In,Ga)As quantum well of the same average thickness and coincided in energy with the absorption peak in calorimetric absorption spectrum. The PL peak energy depended on both spacer thickness and number of (In,Ga)As deposition cycles and ranged at 8K from 1.11 to 1.28 eV and from 0.97 to 1.075 eV for InAs and $In_{0.5}Ga_{0.5}As$ VECOD's respectively.

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SIMULATION OF STM IMAGES OF ADATOMS ON GALLIUM ARSENIDE

Th. Laloyaux, H. Tang and J.-P. Vigneron

Facultés Universitaires Notre-Dame de la Paix, Namur, Belgium

In the study of growth mechanisms, it is interesting to observe the surfaces with a scanning tunneling microscope. This contribution is particularly devoted to the GaAs (110) surface. During the growth of this surface, the deposited Ga and As atoms are first adatoms. Because the STM observations are related to the electronic structure and not directly to the atomic geometry, the experimental results are not always easy to interpret. Therefore, realistic simulation methods of the STM measurements are useful.

Here, we present simulations of STM images of Ga and As adatoms on GaAs (110), in the framework of the Tersoff-Hamann theory of STM [J. Tersoff & D. R. Hamann, Phys. Rev. Lett. **50**, 1998 (1983)]. The local density of states of the sample surface is calculated using the density functional theory, with the local-density approximation. The ions are represented by non-local separable pseudopotentials and the wavefunctions are expanded in a plane-wave basis set. The surface is modelized by a slab.

We present simulated images for both positive and negative biases, for either Ga or As adatoms sitting on GaAs (110). Current-voltage characteristics are also computed for various positions of the STM tip. These results are compared with experimental data.

NANOLITHOGRAPHIC PATTERING OF THIN METAL FILMS WITH A SCANNING PROBE MICROSCOPE

S. Melinte, B. Nysten and V. Bayot

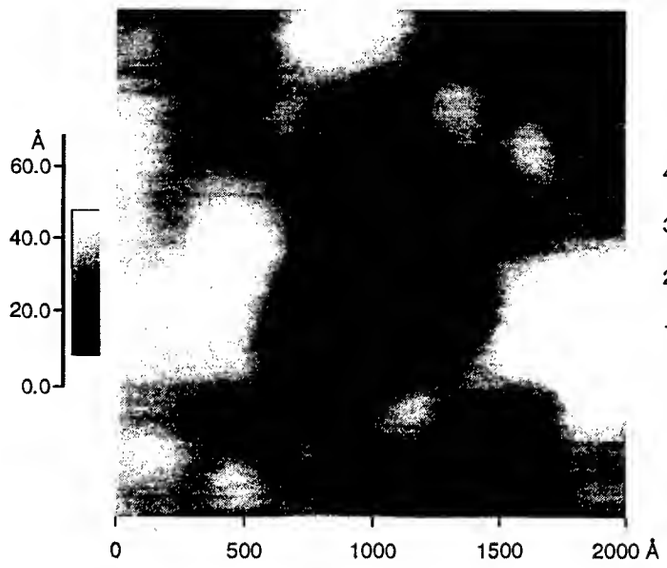
Unité de Physico-Chimie et de Physique des Matériaux

Université Catholique de Louvain

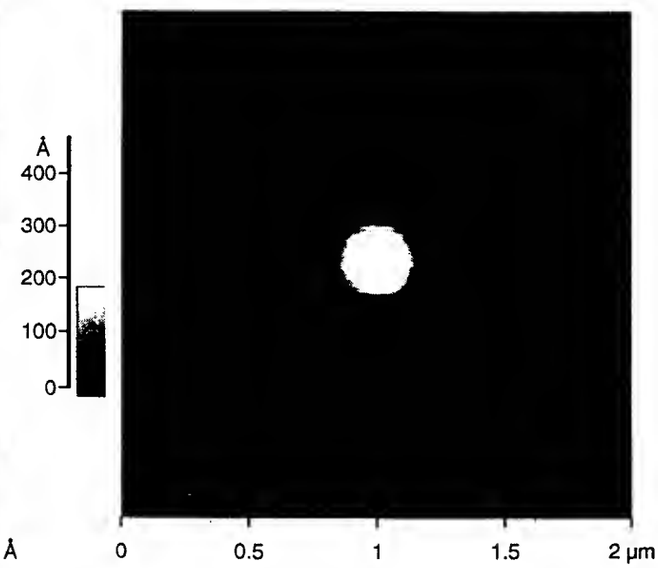
Place Croix du sud 1, B-1348 Louvain-la-Neuve, Belgium

ABSTRACT

Using an AFM/STM operating in air and/or in a controlled atmosphere (N_2) we locally modify thin films (<5nm) of e-beam deposited Cr and Ti onto a Si substrate. We use a metallised tip and the sample is biased positively with respect to the tip. Depending on the nature of the metallised tip and on the writing conditions, pits or metal oxide mounds are created with dimensions below 100nm. Both types of modifications reach metal/substrate interface. The potential of the novel technique is demonstrated by measuring the patterned metallic stuctures.



Pit made in a 4 nm thick Cr layer with a Cr coated tip keeped in air and using an bias voltage V_{sample} = +10V during 10 sec.



Mound of metal oxide made on a 4nm thick Cr layer with a freshly coated Cr tip. Pulse duration was 5sec and the bias voltage was V_{sample} = +9V.

Detection of Optical and Electronic Properties of Low Dimensional Structures by Surface Photovoltage Spectroscopy

N. Ashkenasy[1], L. Kronik[1], M. Leibovitch[2], S. Gorer[3], G. Hodes[3]

Y. Rosenwaks[1], M. C. Hanna[4], Prakhya Ram[2] and Yoram Shapira[1]

Low dimensional structures have been studied using surface photovoltage spectroscopy (SPS). This method uses the well known Kelvin probe technique to monitor the changes in the surface work function due to illumination. It is contactless, nondestructive and ambient insensitive.

The technique detects *all* the energy level transitions between heavy hole and electron states in quantum well structures (multi-quantum well structures as well as superlattices), with high accuracy as compared to photoluminescence measurements, and in excellent agreement with theoretical calculations. In addition, information about built-in voltages in the different layers is obtained, resulting in the energy band diagram of the structures.

The technique was also employed for studying the photovoltaic effect of quantum dot films. Direct evidence for the existence of surface-localized optical absorption in semiconductor quantum dots is presented. The cardinal role of surface states in determining the photovoltaic properties of quantum dot films is demonstrated. The physical mechanisms of photovoltage formation in quantum dot films are discussed.

[1]*Department of Electrical Engineering-Physical Electronics, Faculty of Engineering, Tel Aviv University, Ramat Aviv 69978, Israel.*

[2]*Physics Department, Brooklyn College, CUNY, Brooklyn, New York 11210, U.S.A.*

[3]*Department of Materials and Interfaces, Weizmann Institute of Science, Rehovot 76100, Israel.*

[4]*National Renewable Energy Laboratory, Golden, Colorado 80401, U.S.A.*

An Investigation Of Coherent Current Injection From Ohmic Spikes In Nanostructures.

R.P.Taylor[1,2], R.Newbury[1,2], A.S.Sachrajda[2], Y.Feng[2] P.T.Coleridge[2] and J.P.McCaffrey[2]

[1]*School of Physics, University of New South Wales, Sydney, 2052, NSW, Australia.*

[2]*Institute for Microstructural Sciences, National Research Council, Ottawa, KIA OR6, Canada.*

Widespread interest in the two dimensional electron gas (2DEG) system located at the interface of AlGaAs/GaAs heterostructures has focussed on combining high electron mobilities with submicron device sizes. However, advances made in guiding electrons through intricate regions within the semiconductor have not been matched by refinements to the components which inject the electrons into the semiconductor. "Ohmic contacts" haven't been incorporated as intrinsic parts of nanostructures, either as "local" current injectors or as patterned contacts designed to shape the nanostructure geometry. The mechanism by which the electrons are injected from the Ni-Au-Ge surface metallisation into the 2DEG, and whether the metallisation pattern can be matched in the plane of the 2DEG, are critical issues. We demonstrate the potential for incorporating shaped ohmic contacts into nanostructure designs using a unique device which induces a controlled topological transition between a Corbino disk and Hall bar. Transmission electron microscopy and magneto-transport techniques are used to investigate a novel process where electrons are injected from an array of spikes which extend down from the surface metallisation to penetrate the 2DEG. For temperatures below 4K, quantum waves associated with the injected electrons are shaped by the spikes and determine the contact resistance through coherent interference processes similar to the highly topical effects currently investigated in quantum dots. We discuss the implications of the presence of these "natural" nanostructures in Ohmic contacts.

Vanishing of the Mott Transition in Semiconductor Nanocrystals

G.Tamulaitis, S.Juršėnas, G.Kurilčik, and A.Žukauskas

Institute of Materials Science and Applied Research, Vilnius University,

Naugarduko 24, 2006 Vilnius, Lithuania

Mott transition in semiconductors, i.e. a transformation of exciton gas (dielectric phase) into electron-hole plasma, EHP, (metallic phase), is a fundamental consequence of many-body interaction. This interaction is strongly effected by quantum confinement in low-dimensional structures. By means of photoluminescence spectroscopy, we investigated the peculiarities of the Mott transition in CdS nanocrystals embedded in glass. The average radii a of nanocrystals in the set of samples ranged from 100 nm (bulk-like nanocrystals: $a >> a_B$, a_B is exciton Bohr radius) down to 4.5 nm ($a \cong a_B$) when quantum confinement effect is strong.

Because of the difference between exciton and electron effective masses, the blue shift of exciton luminescence band due to quantum confinement is significantly weaker than that of the band caused by the recombination of a free electron-hole pair. These two bands, fairly well separated in the luminescence spectrum of small nanocrystals, were utilized to elucidate the dynamics of the quasiparticles originating their appearance.

Investigations under cw and quasistationary excitation as well as under excitation with 30 ps pulses of YAG:Nd^{3+} laser radiation allow us to conclude a strong dependence of the Mott transition on nanocrystal radius. In bulk-like nanocrystals we observe usual transition from exciton gas to EHP when the band gap renormalization due to many-body interaction becomes as large as the exciton binding energy. The decrease of the nanocrystal radius down to $a \approx 4a_B$ causes a diminishing of the many-body interaction and an increase of the critical density of the Mott transition.

Qualitatively new situation was observed in the nanocrystals with radii in the range $a_B \le a \le 4 \cdot a_B$. Here, the increase of excitation intensity does not initiate the transition of the exciton gas to the system of free electrons and holes. These two phases coexist in the nanocrystal even at densities of free pairs drastically exceeding the density at thermal equilibrium with exciton system. The coexistence of two phases is explained in terms of decreasing effectiveness of screening by confined quasiparticles.

Wednesday

WeA Symposium on microcavities I

PHOTONIC BANDGAP STRUCTURES OPERATING AT OPTICAL WAVELENGTHS

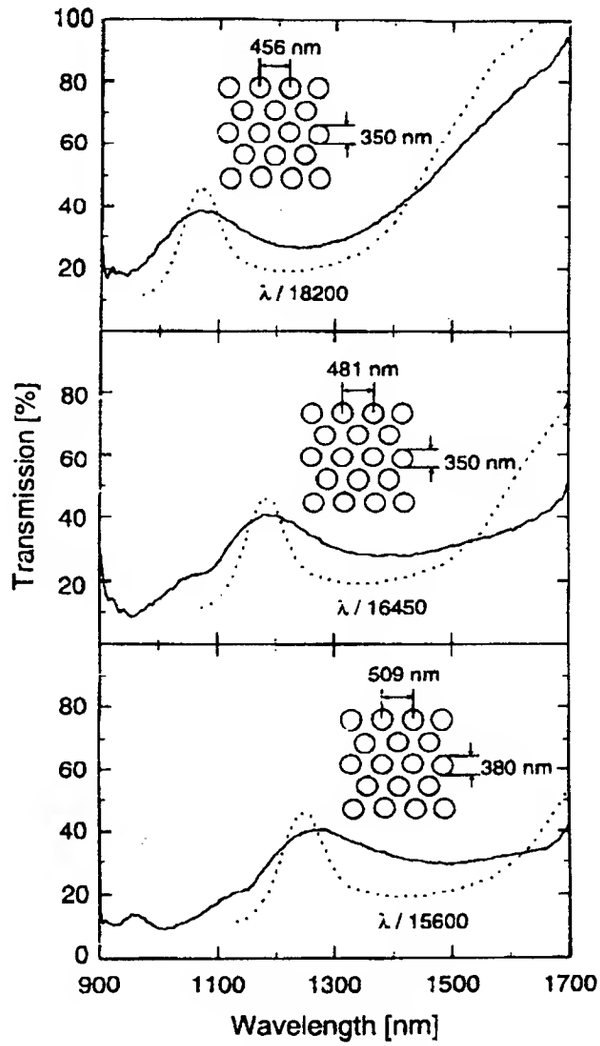
Vincent Arbet-Engels2,
A. Scherer1,
C.C. Cheng1,
and E. Yablonovitch2,

1 Electrical Engineering Department
California Institute of Technology
Pasadena, CA 91125

2 Electrical Engineering Department
University of California, Los Angeles
Los Angeles, CA 90095-1594

Abstract

We describe the fabrication of three-dimensional photonic crystals with photonic bandgaps lying in the near infrared region of the electromagnetic spectrum. In fabricating these nanostructures through electron beam lithography followed by dry etching, we have produced photonic crystals with a depth up to four layers. The spectral transmission of these photonic crystals was tuned by lithographically controlling their spatial periodicities. We believe we have seen the first optical signature for 3-dimensional photonic crystals operating at such short wavelengths. In the present work, we discuss the elaborate processing steps used to synthesize these three-dimensional dielectric structures and we will analyze their transmission spectra in comparison with a macro-machined microwave scalemodel.



MOTIONAL NARROWING IN SEMICONDUCTOR MICROCAVITIES

D. M. Whittaker*, P. Kinsler, T. A. Fisher, M. S. Skolnick, A. Armitage and A. M. Afshar.
Department of Physics, University of Sheffield, Sheffield. S3 7RH. UK.

J. S. Roberts, G. Hill and M. A. Pate.
Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield.
S1 3JD. UK.

Microcavities offer new possibilities for engineering the opto-electronic properties of semiconductors. Just as a quantum well confines electrons and excitons, a microcavity provides two dimensional confinement for photons. This extra control allows us to investigate new physics involving exciton-photon interactions, as well as opening the way for new devices, such as low threshold lasers.

The most significant consequence of using a microcavity is that the exciton and cavity photon modes are close to resonance for optically active states. The polariton coupling between the two modes can be observed spectroscopically as an anti-crossing between the corresponding features as they are tuned through resonance. We describe our investigation of this anti-crossing by varying the temperature to tune the exciton through the cavity mode, and using electric and magnetic fields to change the strength of the exciton-photon interaction.

An important property of the cavity photon, and also of the polariton, is its low in-plane effective mass, $\sim 10^{-5} m_0$, compared to the normal exciton mass, $\sim m_0$. This makes a big difference to the way the excitations interact with disorder in the quantum well to produce the inhomogeneous broadening of the spectra: the large mass exciton behaves essentially classically, whereas the small polariton mass means that quantum mechanical averaging over the disorder potential occurs. The averaging causes a significant decrease in the inhomogeneous broadening, a phenomenon known as motional narrowing. We present a simple scaling theory of motional narrowing, which successfully predicts how the line widths of our spectra vary as the system is tuned through resonance.

Motional narrowing represents a consequence of 'accidental' in-plane scattering of polariton modes. It should also be possibe to pattern a microcavity to introduce deliberate in-plane scattering, and exploit the low photon effective mass to produce photon band-structure effects. We suggest methods of patterning which should be capable of producing localised photon states, a possible route to low threshold laser devices.

*Present address: Toshiba Cambridge Research Centre, 260 Cambridge Science Park, Milton Road, Cambridge, CB4 4WE, UK.

Light Emission from Excitons in Semiconductor Microcavities

Ross P. Stanley, R. Houdré, and M. Ilegems

Institut de Micro et Optoélectronique,
Départment de Physique
EPFL, Switzerland

The light-matter interaction can be strongly influenced by the local optical environment. The resulting phenomena can be order on a sliding scale of increasing light matter interaction. The weak coupling regime starts with the redistribution of spontaneous emission. This purely geometrical effect can be used to reduce emission linewidth and increase directionality, and accounts for the majority of microcavity phenomena. The manipulation of the spontaneous emission using cavities has produced record efficiencies for planar LED's.

The next level occurs when the optical mode is confined to a volume of about one wavelength cubed, then the rate of spontaneous emission can also be significantly altered; either enhanced or suppressed depending on the overlap between the optical mode and the emitting medium.

Finally, if the cavity mode is resonant with a system having discrete energy levels such as a quantum well exciton, then the very energy levels of both cavity and excitons may be altered. This is the strong coupling regime where there is a unique blend of cavity optics and semiconductor physics.
Since the first observation of the strong coupling in 1992 [1], the field has rapidly matured, driven on by critical experiments and backed up by theoretical modelling of increasing completeness. We have moved from the simple but instructive picture of coupled harmonic oscillators to that of cavity polaritons and we now see a range of physical phenomena unique to excitons in semiconductor microcavities. In particular we shall discuss the emission of light by cavity-polaritons, as measured expeimentally and calculated from theory.

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WeB Symposium on microcavities II

Electron- and Photon-Manipulation in Microcavities and Practical Applications

Masamichi Yamanishi
Department of Physical Electronics, Faculty of Engineering, Hiroshima University, Kagamiyama 1-chome, Higashihiroshima 739, Japan

Spontaneous emissions from atoms can be controlled by squeezing vacuum-field fluctuations of the photon fields surrounding the atoms in both spatial and frequency domains. It is of great importance to manipulate electron system as well in order to alter spontaneous emissions, from both the fundamental and application points of view. This can be easily done in semiconductor microstructures by a combined utilization of the quantum confined Stark effect (QCSE) and cavity quantum electrodynamics for manipulating electron- and photon-systems, respectively. In the talk, we demonstrate our recent results on physical phenomena such as high transfer efficiencies of spontaneous emissions, $\beta_t \sim 24\%$, and cavity-induced fractional changes of exciton (radiative) decay time, 30% even with planar Distributed Bragg reflector (DBR) cavities, the systematic results which were obtained with the benefit of the combined quantum manipulation [1]~[7].

Obviously, the scheme for the simultaneous quantum manipulation gives us a very powerful diagnostic tool for systematic investgation of the cavity-quantum-electrodynamics in semiconductor microcavities. The same scheme is also expected to lead to evolutional device-concepts for highly efficient, high-speed spontaneous light emitters [8].

In addition, we demonstrate a clear evidence of the influence of oscillator strength on exciton-polariton mode splitting in the planar DBR cavities [9]. This has been, again, done by taking advantage of the large tunability of the oscillator strength by QCSE. A possible application of the cavity polartion concept in the presence of electric field such as THz-electromagnetic wave generator [9] will be discussed in the presentation.

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Exciton-polariton dynamics in a GaAs bulk microcavity

S. Ceccherini, M. Gurioli, F. Bogani, M. Colocci

Dipartimento di Fisica, Unità INFM and LENS, L.go E. Fermi 2, I-50125 Firenze (Italy)

A. Tredicucci, F. Beltram

Scuola Normale Superiore and INFM, Piazza dei Cavalieri 7, I-56126 Pisa (Italy)

L. Sorba

Laboratorio Tecnologie Avanzate, Superfici e Catalisi INFM, Padriciano 99, I-34012 Trieste (Italy)

The response of the excitonic state to an incoming radiation pulse is deeply altered in a microcavity system, owing to the strong coupling with the electromagnetic mode. Recently, a new type of structure in which the whole cavity material is the active medium has been proposed, and the exciton Rabi splitting has been directly observed also in the bulk case.
We shall present a full analysis of the exciton dynamics in a GaAs $\lambda/2$ bulk microcavity following excitation by an ultrafast laser pulse. At low excitation levels, a linear regime is established and the strongly coupled system oscillates between its exciton and photon component. Rabi oscillations have been detected using an interferometric technique which probes the coherent part of the signal. Dephasing and decay times have also been measured for various exciton-cavity detunings. At higher intensities, population effects begin to show up reducing the exciton oscillator strength and causing the vanishing of the Rabi splitting; the recovery times have also been measured with time resolved pump and probe experiments. At the same time, evident non-linearities in the input-output characteristic of the optical functions have been observed. Differences with respect to standard quantum well microcavities, arising from the large extension of the optically active material and from the stationary nature of bulk excitonic polaritons will be discussed in the framework of theoretical calculations performed within the transfer-matrix method.

TWO DIMENSIONAL EXCITON POLARITONS IN MICROCAVITIES WITH EMBEDDED QUANTUM WIRES

A.V.Kavokin, E.L.Ivchenko, M.A.Kaliteevski, M.R.Vladimirova

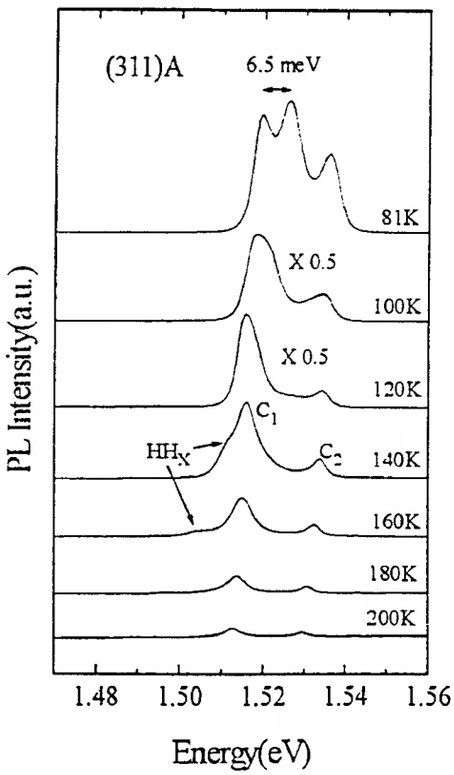
A.F.Ioffe Physico-Technical Institute, 26 Politechnicheskaya, 194021, St-Petersburg, Russia, fax: (7812)247-10-17, e-mail: kavokin@coherent.pti.spb.su

Combining the transfer matrix method and non-local dielectric response theory we have analyzed the dispersion of 2D exciton-polaritons in semiconductor microcavities with embedded periodical gratings of quantum wires. Substantial optical anisotropy of the quantum wire system is shown to result in anisotropic Rabi-splitting of confined polariton branches. In the oblique incidence geometry an appearance of additional polariton modes of different nature is found. Additional modes are attributed to (i) Z-polaritons excited by TM-polarized light mode, and (ii) light waves resonantly scattered by the grating of wires. Resonant light diffraction on the quantum wires takes place for long-period gratings of wires and results in substantially enriched polariton spectra of microcavities. If eigen energies of corresponding 2D exciton-polariton modes in a cavity are well-separated, interaction of cavity photons with quantum wire excitons can be described in a usual two-harmonic-oscillator model. Of particular interest is the opposite case of strong interaction between reflected and scattered light waves due to their confinement by the cavity mirrors. This is realized, for example, in case of diffractional back-scattering of light. Solving exactly the Maxwell equations for the grating of wires and applying 4×4 transfer matrix formalism we have obtained the dispersion equation for four 2D polariton modes arising in this case. Rabi-splitting between upper and lower modes exceeds the splitting in two-oscillator system by a factor of $\sqrt{2}$. These analytical findings are confirmed by a numerical modelling. The calculated reflection, absorption, and diffraction scattering spectra show from 2 to 4 resonant features corresponding to eigen polariton modes. The optimal design of microcavities with quantum wires suitable for observation of diffraction effects requires lateral wire sizes in range of 50-100 nm and interwire spacing of 150-250 nm.

Temperature tuning of exciton-photon coupling in a microcavity grown on a (311)A GaAs substrate

F.M.Matinaga, L.A.Cury, E.C.Valadares, M.V.B.Moreira, W.N.Rodrigues and A.G.de Oliveira, J.M.C.Vilela‡, M.S.Andrade‡, J.A.Sluss‡
Departamento de Física - Instituto de Ciências Exatas - Universidade Federal de Minas Gerais, Caixa Postal:702, 30161-970 Belo Horizonte, Minas Gerais, Brazil.
‡ Fundação Centro Tecnológico de Minas Gerais - CETEC, Av. José Cândido da Silveira, 2000 Horto, 31170-000 Belo Horizonte, Minas Gerais, Brazil.

Rabi splitting in a microcavity grown on a (311)A GaAs substrate was observed for the first time using photoluminescence (PL). This splitting is larger than that observed in a similar structure grown on a (100) GaAs substrate[1], in agreement with the expected larger binding energy of excitons confined in higher index quantum wells[2]. Our microcavity structure was grown by MBE and its good morphological quality was verified by atomic force microscopy (AFM). It consists of two AlAs/$Al_{0.15}Ga_{0.85}As$ DBR mirrors, and the active region is formed by three GaAs 100Å quantum wells sandwiched by two $Al_{0.3}Ga_{0.7}As$ spacer layers.



The PL characteristics of this microcavity were measured in the range 81K-200K, as shown in the figure. We observe clearly the evolution with temperature of the heavy hole exciton (HH_x) emission line and two cavity modes (C_1 and C_2). The HH_x emission line shifted six times more than the cavity modes. The crossover of the HH_x line with the C_1 cavity mode occurs around 100K, and a Rabi splitting of Ω=6.5 meV is observed at 81K.

The present study demonstrates unambiguously that PL can be used to probe Rabi splitting in semiconductor microcavities tuned by varying the temperature, in addition to the usual photoreflectance and transmission measurements.

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Thursday

ThA Low-dimentional structures and quantum wires

Recent Progresses in quantum structures

H.Sakaki, *University of Tokyo*

Abstract not received.

CONTROLLED DISLOCATION SLIPPING : AN ORIGINAL METHOD TO CREATE MULTI-QUANTUM-WIRE STRUCTURES

L. Ressier, J.P. Peyrade, F. Voillot, C. Vieu(1)

Laboratoire de Physique des Solides de Toulouse - INSA (FRANCE)

(1) L2M-CNRS Bagneux (FRANCE)

We propose a new method to create one dimensional (1D) structures using dislocation as an atomic scale saw to cut a 2D structure into a multiple-quantum-wire structure. This simple method, based on dislocation slipping induced by plastic deformation, is not material specific and can be applied to any crystalline system without any loss of the active layer. We have verified the efficiency of the method on a GaAs/GaAlAs heterostructure grown by Molecular Beam Epitaxy on a (001) GaAs substrate (Fig.1).

Photoluminescence (PL) spectra on the deformed heterostructure reveal a 10 meV blue shift of the exciton peak, compared to the quantum well PL spectra. The distributions of the quantum wire widths Lx and of the shifts Δ between the quantum wires are studied by fractal analysis of Atomic Force Microscopy (AFM) pictures and statistical analysis of Transmission Electron Microscopy cross section (XTEM) observations : they show a communicating multiple-quantum-wire structure (or lateral superlattice) composed of coupled (Δ<Lz) 100-150 Å width quantum wires. A calculation based on the tight-binding perturbation model confirms the creation of such a lateral superlattice by correlating the PL results with microscopy observations.

In order to decouple quantum wires and monitor width Lx, we submit, prior to dislocation slipping, the surface of the heterostructure to local stresses induced by a Si_3N_4 standard lithography-created grid (Fig.2). Our first XTEM and AFM observations on a deformed GaAs/GaAlAs heterostructure with a Si_3N_4 grid on its surface confirm the theoretical calculations.

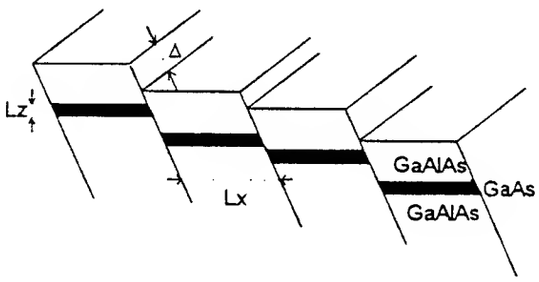

Fig.1 : Multiple-quantum-wire structure

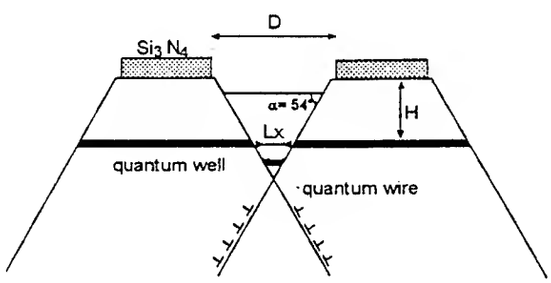

Fig.2 : Controlled dislocation slipping

Uniform GaAs quantum wires formed on vicinal GaAs(110) surfaces by two-step MBE growth

M. Takeuchi, T. Takeuchi, Y. Inoue, T. Kato, K. Inoue and H. Nakashima*
The Institute of Scientific and Industrial Research, Osaka University,
8-1 Mihogaoka, Ibaraki, Osaka 567, Japan

P. Fischer and J. Christen
Fakultät für Naturwissenschaften, Otto-von-Guericke Universität Magdeburg,
Universitätplatz 2, D-39016 Magdeburg, Germany

M. Grundmann and D. Bimberg
Institut für Festkörperphysik, Technische Universität Berlin,
Hardenbergstarß 36, 1 Berlin 12, Germany

We have previously demonstrated that GaAs quantum wires (QWRs) are naturally formed by molecular beam epitaxy (MBE) on vicinal GaAs(110) surfaces with coherently aligned giant growth steps due to thickness modulation at the step edges [1]. Broad photoluminescence (PL) peaks were observed for these GaAs QWRs indicating the nonuniformity of the QWR structures. In this paper, we report the method to improve the GaAs QWR uniformity based on the growth-temperature dependence of the step structures.

Samples were grown by gas-source MBE using AsH_3 on vicinal GaAs(110) misoriented toward (111)A, and GaAs(100) for comparison. The giant growth steps were formed at 500°C by the growth of a 5-period 30 nm-$Al_{0.5}Ga_{0.5}As$/30 nm-GaAs multilayer on a 200 nm-GaAs buffer layer. Succeedingly, a 30 nm-$Al_{0.5}Ga_{0.5}As$/*t* nm-GaAs/30 nm-$Al_{0.5}Ga_{0.5}As$ quantum well (QWL) was grown at 500°C (Samples A) or at 550°C (Samples B). In other word, Samples B were grown by two-step growth procedure, in which the growth temperature was changed during the growth.

Since sharp giant growth steps are formed at lower temperature and large thickness modulation is observed at higher temperature, we employed two-step growth to improve the QWR uniformity. The PL peaks of Samples B are more red-shifted and narrower than those of Samples A, indicating that the higher-temperature growth enhances the thickness modulation and the layer thickness at the step edges becomes thicker. Narrower PL peaks of Samples B show the improved uniformity of the QWR structures, which is also confirmed from cathodoluminescence images.

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* corresponding author, phone: +81-6-879-8410, fax: +81-6-879-8414

Breakdown Of The One-Electron Picture In Low-Dimensional Electron Systems : Spectral Holes And Singularities At The Fermi Edge Of Photoluminescence Spectra.

T. Mélin and F. Laruelle

Laboratoire de Microstructures et de Microélectronique, C.N.R.S.,

B.P. 107, 92225 Bagneux Cedex, France.

Fax : + 33 1 42 31 73 78. E-mail : thierry.melin@bagneux.cnet.fr

In a one-electron approximation, the low-temperature photoluminescence (PL) linewidth of a degenerate electron system (DES) is assigned to the Fermi energy. It is known however that many-body interactions significantly alter the shape of the PL spectrum at the Fermi edge [1]. We report here on the clear identification of the Fermi sea shake-up at the Fermi edge, a process formerly identified on the low-energy side of the PL line [2]. This leads to sizeable corrections between the PL linewidth and the Fermi energy (up to 5 meV or 1.5×10^{11} cm^{-2} for the sheet carrier density).

We use GaAs/AlAs Lateral Superlattices (LSL) grown on vicinal surfaces which provide two-dimensional DES with a strong in-plane lateral modulation, close to the Fermi energy (25 meV) in amplitude and to the Fermi wavelength (30 nm) in periodicity. In tilted LSLs, we control the overlap between electrons and photocreated holes through a tunable coupling of Fermi electrons with the E_2 subband which has a stronger overlap (2 times) with photocreated holes in real space along the growth axis, because of asymmetric doping of the well. In addition, this coupling occurs in k-space at the zone center through a careful adjustment of both Fermi wavelength and lateral periodicity. This results in a greater in-plane overlap in k-space with photocreated holes (14 times).

We observe either a hole or a singularity at the Fermi edge of the 2K PL spectrum when Fermi electrons are weakly or strongly coupled to the E_2 subband depending on the LSL tilt. Both spectral anomalies extend over 5 meV (one GaAs effective Rydberg) below the Fermi level. Most intense singularities can be fitted using a finite temperature formula [3] and a phase shift $\delta \approx 0.21\ \pi$ with a peak 1 meV below the Fermi level. In case of rounded edges, the Fermi energy is deduced from the Moss-Burnstein shift between the PL peak and the first shoulder in PL excitation. It clearly identifies a spectral hole in luminescence 5 meV below the Fermi energy. The Fermi edge critical exponent changes from negative to positive in qualitative agreement with recent theories [4]. Additional confirmations of shake-up processes at the Fermi edge come from the PL linear polarization spectrum. The linear polarization induced by the LSL potential is parallel to the step edges of the vicinal surface. It gets more intense towards the higher energies and exhibits a sudden drop to zero at the Fermi edge because of the hole scattering in k-space during the Fermi sea shake-up [2]. A final evidence of shake-up processes is the threshold energy of the PL excitation spectrum. It precisely coincides both with the extremum polarization energy and with the onset of the PL hole or singularity 5 meV below the Fermi level and an indication of a threshold energy for many-body interactions since this is much greater than $3k_BT$.

In summary, many-electrons processes are responsible for spectral anomalies in emission, polarization and absorption of low-dimensional DES. They alter the one-electron-approximation of the Fermi energy determination by optical methods in a non negligible way.

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Large Excitonic Confinement in Asymmetric Quantum T-Wires

J. Hasen, L.N. Pfeiffer, A. Pinczuk, H.U. Baranger, K.W. West, B.S. Dennis

Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974

An asymmetric Quantum T-Wire (QTWR) is formed at the intersection of two different GaÂs Quantum Wells (QW). We measured the photoluminescence and photoluminescence excitation using a microscope with high spatial resolution. The introduction of an asymmetry in the design of the QWs allows us to compensate for the different effective masses of the heavy holes in the 100 and 110 directions. We find that the confinement energy for excitons in the asymmetric QTWR is 40 meV, which is greater than previously published reports on symmetric QTWRs. Consequently, the confinement energy exceeds kT at room temperature, which appeals to device applications. Furthermore, the confinement energy is greater than the LO phonon energy, a feature which may improve the capture rate of the QTWR and decrease the escape rate at higher temperatures. Finally, using the results from calculations, we estimate the binding energy of the exciton to be about 20 meV, which is substantially larger than the binding energy in QWs. This result agrees with theoretical predictions of an increase in exciton binding energy in 1D confinement.

CONDUCTANCE ANOMALIES IN STRAINED QUANTUM WIRES: THE CASE OF PbSe AND PbTe

G. Grabecki, J. Wróbel, T. Dietl, M. Sawicki, and T. Skośkiewicz
Institute of Physics, Polish Academy of Sciences
al. Lotników 32/46, PL 02 668 Warszawa, Poland
E. Papis, E. Kamińska, A. Piotrowska
Institute of Electron Technology
Al. Lotników 32/46, PL 02 668 Warszawa, Poland
Y. Ueta, G. Sprinholtz, and G. Bauer
Institut für Halbleiterphysik, Johannes Kepler Universität Linz
A 4040 Linz, Austria

Recent works[1,2] have shown that the magnetoconductance of Hall bridges patterned from epitaxial films of PbSe and PbTe exhibits a number of novel features. In particular, it has been found that the amplitude of aperiodic conductance fluctuations is abnormally large[1]. At the same time, the presence of a nonlocal conductance has been put into evidence, and assigned to the existence of edge channels.[2]

In order to shed some light on the phenomenon, we have undertaken a systematic study of magnetoconductance in microstructures of both PbSe and PbTe as a function of temperature in the range 30 mK – 300 K, electron concentration between 1×10^{16} and 6×10^{17} cm^{-3}, and the line width down to 0.5 μm. PbTe:Bi films with thickness of 0.5 μm were grown onto BaF_2 substrate with $Pb_{0.94}Eu_{0.06}Te$ buffer layer, while PbSe films with thickness of 1.7 μm were deposited directly onto BaF_2 substrate. The wires had the form of six-terminal Hall bars with two side gates. They were fabricated by photo or electron-beam lithography, followed by either Ar ion milling or wet etching.

Based on our data we suggest that a known difference between the thermal expansion coefficients of the substrate and the film below 200 K (which causes an overall biaxial tensile strain in the epilayer of the order of $1\text{-}2\times10^{-3}$) is responsible for the observed transport anomalies. This difference leads to biaxial strain, whose magnitude varies however, substantially near the wire edges. The effect of such nonuniform strain on electron transport is particularly large in the studied system due to its large piezoresistivity associated with the strain-induced electron redistribution between the valleys. This model explains the existence of edge channels with the enhanced conductance and, in particular, the appearance of the nonlocal conductance below 200 K. The presence of edge channels is documented further by studies as a function of the line width, by a strong sensitivity of the conductance to the side-gate voltage as well as by a large magnitude of the aperiodic fluctuations and of the transverse magnetoresistance.

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Carrier confinement in self–ordered AlGaAs vertical quantum wells

E. Martinet, A. Gustafsson, G. Biasiol, F. Reinhardt and E. Kapon
Institut de Micro et Optoélectronique, Département de physique, EPFL, CH-1015 Lausanne, Swizerland, Fax: 0041/21-693 54 80, e-mail Martinet@eldpb.epfl.ch

$Al_xGa_{1-x}As$ vertical quantum wells (VQWs) formed by self-ordering during organometallic chemical vapour deposition (OMCVD) on V-grooved substrates [1,2] show polarization anisotropy of photoluminescence (PL) spectra [2], normal incidence intersubband transitions [3] and lasing with beams polarized in the VQW plane [4]. Here we report the direct observation of quantum confinement in VQWs grown by low pressure OMCVD as evidenced by PL excitation (PLE) experiments. Dark field transmission electron microscope (TEM) cross sections of the VQW structures (Fig. 1) show distinct VQW branches, with the outermost ones separated by 5 to 35nm for x=0.7 to 0.15. Evidence for the higher Ga mole fraction at the dark-contrast bands in the TEM images is provided by cross-sectional atomic force microscopy [5,6]. PL spectra show emission from the VQW with only 5meV linewidth (Fig. 2). Polarized PLE spectra, detected at the VQW PL line, exhibit the anisotropy associated with e-hh and e-lh transitions (Fig. 2). These transitions were modelled using a double–well profile deduced from scans of the TEM images (Fig. 3). The spectra obtained with pump polarization normal to the VQW planes correspond well to the calculated e-lh transitions (triangles). The parallel polarization spectra correspond to e-hh (circles) and e-lh mixed states. The 5 meV calculated difference between e_1-hh_1 and e_1-lh_1 is in agreement with the measured value. The effect of confinement in carbon acceptor related PL lines in these structures will also be discussed.

Fig. 1

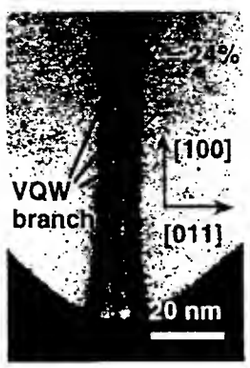


Fig. 2

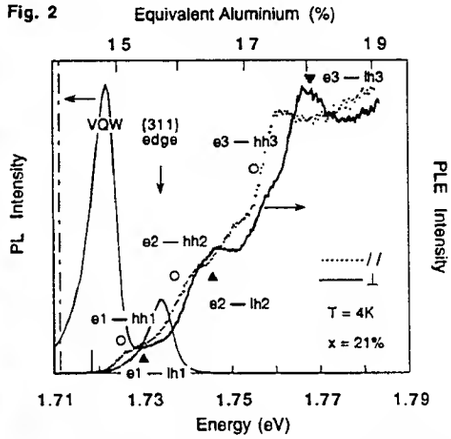
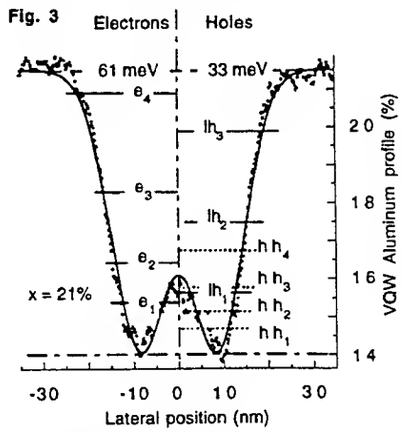


Fig. 3



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Exciton diffusion dynamics in quantum nanostructures on V-groove patterned substrates

N. Usami, W. Pan*, H. Yaguchi*, K. Onabe*, and Y. Shiraki

RCAST and the Faculty of Engineering, the University of Tokyo*
4-6-1 Komaba, Meguro-ku, Tokyo 153, Japan

Exciton diffusion dynamics in quantum nanostructures on V-grooved substrates, which would greatly affect the optical properties, are investigated on two different systems; SiGe/Si quantum well (QW) structures on V-grooved Si substrates and AlGaAs spontaneous vertical QW (SVQW) structures on V-grooved GaAs substrates.

Three pairs of no-phonon (NP) and transverse optical (TO) phonon replicas, which are assigned as (111) facet QWs, quantum wires (QWR) at the bottom of the V-groove, and the (100) QWs, are observed from 34Å $Si_{0.82}Ge_{0.18}$ QWs on V-groove patterned Si substrates with periods of 2-4 μm. The decay time of the luminescence arising from the (111) facet QWs was found to be strongly dependent on the V-groove period, and the shorter decay time was observed with decreasing the V-groove period. Temperature dependence showed that the decay time of the (111) facet QWs decreases with increasing temperature in the lower temperature region against theoretical prediction for the radiative lifetime of two-dimensional excitons.

The same anomaly was also found in the time-resolved PL study of the $Al_{0.25}Ga_{0.75}As$/V-grooved GaAs with spatial nonuniformity of the alloy composition formed during growth. With increasing temperature, the decay time of the SVQW at the bottom of the V-groove increased, however, that of the outer AlGaAs with less Ga composition decreased as like the SiGe (111) facet QWs. Moreover, anomalous delay of the rise time was found in the SVQW, showing the exciton formation is not the limiting factor of the rise time.

These results are consistently explained in terms of the exciton diffusion toward the bottom of the V-groove. The increase of the diffusion length of excitons with temperature would be explanation for the anomalous decrease of the decay time of the (111) SiGe QWs and the outer AlGaAs. This also suggests that it could be possible to efficiently collect excitons to the bottom of the V-groove at higher temperatures.

papers per title

INTERSUBBAND EXCITATIONS IN PARALLEL QUANTUM WIRES WITH WEAK TUNNELING*

S. E. Ulloa and T. V. Shahbazyan

Department of Physics and Astronomy and Condensed Matter and Surface Sciences Program, Ohio University, Athens, OH 45701-2979, USA

We study collective and single-particle intersubband excitations in a system of quantum wires with weak tunneling. For an isolated wire with parabolic confinement, the Kohn theorem guaranties that the absorption spectrum represents a single sharp peak centered at the frequency of bare confining potential. We show that the effect of weak tunneling between two otherwise perfectly parabolic quantum wires is twofold: (i) tunneling-induced splitting of energy levels causes a dispersion in single-particle excitation frequencies, and (ii) the sharp peak, corresponding to the intersubband plasmon frequency, is shifted by an amount proportional to the mean square splitting. We also demonstrate that the interplay between tunneling and weak perpendicular magnetic field strongly affects the absorption spectrum. In particular, by shifting the energy levels of two wires in opposite directions in k-space, the magnetic field drastically enhances the dispersion of single-particle excitations. The latter leads to a damping of intersubband plasmon for magnetic fields exceeding some critical value. As a result, the sharp absorption peak should acquire a finite width depending on concentration and parameters of the confinement potential, accessible to experiments.

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« Piezoelectric quantum wells as a probe to study charge transfer and band-bending »

E. Vanelle, R. Romestain, R. André, D. Block, J. Cibert and Le Si Dang

Laboratoire de Spectrométrie Physique, Université J. Fourier de Grenoble et CNRS (URA 8),

BP 87, F38402 Saint Martin d'Hères, France

We report here on an original property of piezoelectric quantum wells (QWs) and multiple quantum wells. There, the internal field acts as a bias and this results in a linear Stark effect and consequently in a high sensitivity to any additional electric field. So, when compared to square QWs, the optical properties of piezoelectric ones are much more affected by charge transfer and band bending near the surface linked to the pinning of the Fermi level.

We have developed a fast and powerful numerical method to calculate charge transfer and band bending, and applied it to the case of piezoelectric QWs and multiple QWs.

Samples grown with piezoelectric QWs located at different distance from the surface have allowed us to determine the surface field and consequently the residual doping, by analysing the exciton energy shifts observed on photoluminescence spectra.

The case of the piezoelectric multiple QWs is quite different. Indeed, the potential steps across each QW cannot add up over the whole multiple QWs structure without being screened by charge transfer. We have shown that this screening needs a charge transfer either locally (into each QW from the neighbouring barriers) or at long distance (from the surface to the bottom of the active layer) depending on the residual doping. Since this charge transfer can induce inhomogeneity of the electric field seen by the QWs, we explain the unusual broadening of transmission spectra of multiple QWs close to the surface, as compared to otherwise identical mulitiple QWs with a thick cap layer.

Intersubband absorption in p-doped twinning superlattices: Envelope function approach

M.Tadić and Z. Ikonić

Faculty of Electrical Engineering, University of Belgrade,

Bulevar Revolucije 73, 11000 Belgrade, Yugoslavia

In addition to heterostructure potential and/or doping modulation, change of the orientation of host zink-blende crystal in [111] direction can be efficiently utilized for electron or hole confinement. Elaborate empirical pseudopotential calculations of both the electronic structure and the optical properties of these so called twinning superlattices (TS) were recently carried out.[1] Here, we start from the Luttinger-Kohn Hamiltonian modified in order to encompass the periodical variation of the crystal orientation. It turns out that the change of the stacking sequence manifests in the change of sign of only the (1,2) Hamiltonian matrix element. Effectively, this can be considered as the change of Luttinger parameters, and in optical transitions it is manifested in a finite contribution of the interface envelope function to the transition matrix element. It was recently shown that if the variation of the Luttinger parameters in a classical heterostructure single quantum well is neglected then large errors in calculated normal-incidence absorption may occur.[2] While the variation of the Luttinger parameters of the materials constituting the conventional *p*-doped infrared detectors hardly exceeds 20 %,[3] the twice as large variation encountered in TS contributes significantly not only to bulk states mixing, but also to the intersubband absorption spectrum. Contrary to the classical quantum structures, absorption in the valence band of TS is an order of magnitude larger than in the conduction band, due to the larger interface mixing responsible for the confinement, as stated in Ref. 1. Absorption spectrum in the GaAs obtained by our method agrees well with the results of the comprehensive pseudopotential calculation, at least as far as the position and the width of the absorption peaks are concerned.

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Magnetotransport in Quasi-One-Dimensional Electron Systems Subject to Weak Periodic Modulation and Transverse Electrical Field

Hongqi Xu

Department of Solid State Physics and the Nanometer Structure Consortium, University of Lund, Box 118, S-221 00 Lund, Sweden
Electronic mail address: Hongqi.Xu@ftf.lth.se; Fax: +46-46-2223637

Revelations of quantum magnetoresistance oscillations in various low-dimensional electron systems are among the most significant recent developments in mesoscopic physics. Three well-known examples of these oscillations are the Aharanov-Bohm (AB), Shubnikov-de Haas (SdH) and Weiss oscillations. The AB oscillations observed in phase-coherent conducting rings are periodic in magnetic field B, while SdH and Weiss oscillations observed in pure and periodically modulated two-dimensional electron gas systems, respectively, are periodic in $1/B$. Here we report the prediction for additional types of oscillations. These oscillations can be observed in finite quasi-one-dimensional electron system subject to weak periodic modulation and can be periodic in B^2. This result is from an exact quantum mechanical calculations based on scattering-matrix formalism and an analytical model based on perturbation theory. We explain these oscillations as the transmission through closely spaced discrete energy states corresponding to those in minibands in the infinite system. An expression for the period of these oscillations has been derived. It shows that the period is scaled with $1/a^2$ where a is the periodicity of the modulation. We shall also show that the periodical property of the oscillations can be manipulated using transverse electrical field. We demonstrate that at a strong electrical field these oscillations can be periodic in B with a period that is scaled with $1/a$. We shall finally propose specific experimental tests for these oscillations.

ELECTRONIC PROPERTIES OF HEAVILY BIAXIALLY STRAINED II-VI HETEROSTRUCTURES: BAND MIXING EFFECTS IN CdTe/ZnTe AND ZnSe/ZnTe SUPERLATTICES.

D. BERTHO, F. MALONGA, J.-M. JANCU and C. JOUANIN

Groupe d'Etudes des Semiconducteurs, Université de Montpellier II

CC074, Place E. Bataillon, 34095 Montpellier Cedex 05, France

Abstract:

We present the results of electronic structure calculations for heavily strained II-VI superlattices as CdTe/ZnTe and ZnSe/ZnTe systems. A sp3s* tight-binding model with strain effects and spin orbit interaction is used. In the case of biaxial strain perpendicular to the [001] axis, band-mixings occur at the Γ point of the zinc-blende semiconductors. Light-Hole state is mixed both with the Split-Off valence band (*intra-valence band mixing*) and with the upper-conduction band (*upper-conduction valence inter-band mixing*). These mixing are important for II-VI compounds and thereby modify the electronic properties of strained superlattices. Effects of strain induced inter-band mixing are investigated in two systems. Firstly in CdTe/ZnTe superlattices, this significantly affects the position of the first light-hole to electron transition e_1lh_1. Secondly, we compare the theoretical electronic and optical properties with experiments and we examine the possible offset value of the ZnSe/ZnTe system. Theoretical results agree with experiments in both case.

Optical Properties of Self-assembled InAs Quantum Dots on High-index GaAs Substrates

P.P.González-Borrero, E.Marega Jr., D.I.Lubyshev,E.Petitprez and P.Basmaji

Instituto de Física de São Carlos-Universidade de São Paulo

CP 369, 13960-970 São Carlos, SP, Brazil

The optical properties of InAs QD grown by molecular-beam epitaxy on GaAs (n11)A/B, where n is 1, 2, 5 and 7, and reference (100) substrates, have been studied. For quantum dots (QD) formation, 6 monolayers (ML) were deposited for (100) plane. We have investigated orientation and polarity effects by means of photoluminescence (PL) and polarization measurements. The PL spectra reveal difference on amplitude, integral luminescence, peak position and peak shape. The PL temperature dependence indicates an additional lateral confiment on (100), (211)B, (511)B, (711)B, (111)B, (211)A and (111)A surfaces. This dependence confirms QD formation on these planes. Our results also show an enhancement of the QD onset thermal quenching energy by a factor of 2.5 for these orientations. Based on our QD PL polarization measurements we suppose that QD have well developed microfacet configuration. Contrary, the structure grown on (711)A and (511)A surface does not exhibit QD formation for 6ML although present a broader PL peak related with recombination of a 2D InAs QW.

We believe that the observed polarity (A/B) effects on stress relaxation are caused by different growth mode: Stranski-Krastanow (2D+3D) for (100), (n11)B, (211)A and (111)A surfaces, and Volmer-Weber (2D) for (711)A and (511)A one. The detected orientation and polarity effects on PL properties reveal that In adatom kinetic is an importan mechanism of stress relaxation.

STRUCTURAL AND OPTICAL STUDIES OF HIGH QUALITY $In_xGa_{1-x}As/GaAs$ MULTIPLE QUANTUM WELLS GROWN BY LP-MOCVD

M.Di Dio, M.Lomascolo, A.Passaseo, C.Gerardi and A.Quirini

PASTIS - Centro Nazionale Ricerca e Sviluppo dei Materiali (C.N.R.S.M.), S.S.7 "Appia" Km.714, 72100 Brindisi, Italy.

P.V.Giugno, M.De Vittorio, D.Greco, A.L.Convertino, L.Vasanelli, R.Rinaldi and R.Cingolani

Unità - INFM - Dipartimento di Scienza dei Materiali, Università di Lecce, 73100 Lecce, Italy.

Fax:+39 832 320525; e-mail: devittorio@mvxle2.unile.it

Abstract

We present a comprehensive study of high quality strained $In_xGa_{1-x}As/GaAs$ multiple quantum wells grown by LP-MOCVD. The structural and optical analyses performed by SIMS, X-ray diffraction and optical spectroscopy reveal the excellent quality of these heterostructures. Temperature dependent optical absorption, photoluminescence and magnetotrasmission were used to evaluate the well-width dependence of the major excitonic properties. The samples show sharp excitonic resonances with distinct excited states evolving into Landau-type excited states in high magnetic field. The well-width dependence of the excitonic eigenstates and of the exciton binding energy are well reproduced by envelope-function and variational calculations, also in the presence of external electric field. Non-linear electro-optic modulation induced by the quantum confined Stark effect is demonstrated in a Schottky diode. Our samples show an extremely low reverse voltage switching threshold for the exciton absorption bleaching: 2.5V at 80K and 8.0 V at room temperature.

Theoretical modelling of the exciton energy shift was performed using a variational approach for the exciton wavefunctions under applied electric field. Excellent agreement was found between theory and experiment.

INCREASING OF POLARON EFFECTS IN NANOSTRUCTURES WITH NONPARABOLIC SPECTRUM

I.P. Ipatova, A.Yu. Maslov, O.V. Proshina

A.F.Ioffe Physical Technical Institute, 194021, St.-Petersburg, Russia.

In semiconductors with high ionicity the interaction of carriers with polar optical phonons is strong. It leads to the creation of large radius polarons.

In the present paper the polaron effects in quantum wells, quantum wires and quantum dots are investigated theoretically. In nanostructures under consideration it is established that polaron energies are different for various states of size quantization. These differences are shown to play an important role in optical spectra of nanostructures.

The polaron energies are connected with the static displacements of equilibrium positions of atoms residing within the polaron radius and static polarization of surrounding medium. The differences in static displacements should manifest themselves in Stokes shift and intensive phonon replicas of the optical line of interlevel electronic transitions. The intensities of phonon replicas are calculated using adiabatic potential technique. It is shown that phonon replicas may have the same intensity, in order of magnitude, as the line of direct electronic transition. The multi–phonon effects increase rapidly when the energy of size quantization exceed the phonon energy.

It is found that in II – VI semiconductor nanostructures multi–phonon effects are quite weak in quantum wells. They are stronger in quantum wires and they have the maximum value in quantum dots.

The polaron effects are shown to increase in nanostructures based on narrow–gap semiconductors with high nonparabolicity of the band spectrum. It make it possible to use the optical measurements in investigation of the peculiarities of energy spectrum of carriers.

INFLUENCE OF NANO-SIZED DEFECTS ON SURFACE ENERGY STRUCTURE

Maslova N.S., Oreshkin A.I., Panov V.I., Savinov S.V., Kalachev, A.A*, Rabe J.P.*

Moscow State University, Department of Physics, 119899 Moscow, Russia

*Institute of Physics, Humbolt University, Berlin Germany

In present work the dimensional quantization effects on surface defects have been investigated by STM/STS methods. Such effects appear as additional peaks on experimental curves of tunneling density of states. Correlation interaction between dimensional quantization levels of neighbouring defects has been also discovered. Surface defects have been prepared by remote plasma treatment of HOPG. They are visible in STM images as holes with diameters from 15 to 200 Å.

a) For nanopits with size less than 100 Å (10 nm) the new energy structure (h-states, i.e. holestates, separated by gaps), appears in individual nanopit. As larger is nanopit, as smaller is the gap width.

b) If two nanopits of this size are situated at the distance of 10-20 Å (1-2 nm) or smaller distance, then the mentioned above energy structures inside each pit are splitted into two new energy level sets through the interaction (tunneling transfer) between two initial states inside each nanopit.

Both these effects decrease with defect size and the distance between nanopits increase and disappear when the gap width approaches the value of level broadening. The level broadening is caused by interaction with impurities, substrate and thermal fluctuations.

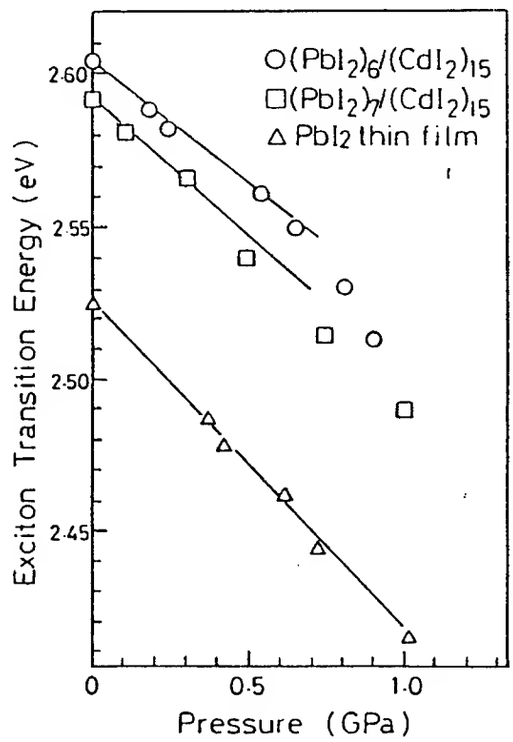
Pressure Effects for Quantum Confinement States in PbI_2/CdI_2 Multi Quantum Wells.

Hiroki KURISU, Toshiya SHIMURA, Setsuo YAMAMOTO and Misturu MATSUURA
Department of Advanced Materials Science and Engineering, Faculty of Engineering,
Yamaguchi University, Yamaguchi, Ube, 755, Japan.

Quantum confinement effects such as subband states appear in quantum well systems. For a decrease in a well width, electron and hole subband energies become higher and then energy separation between these subband energies becomes larger: this yields an increase in an optical transition energy. Under pressure a decrease in a quantum well width occurs and then it is expected that pressure affects a quantum confinement effect significantly. In bulk layered metal halide materials PbI_2 and CdI_2, an interaction between layers arises from van der Waals force, and then lattice constants are easily compressed by applied pressure. The very large change of electronic states in these materials appears on absorption spectra under pressure. Thus, in this paper, we pay attention to PbI_2/CdI_2 multi quantum wells and report that from optical mesurements under pressure the large change in quantum confinement effect in PbI_2/CdI_2 is brought about by a decrease in a well width.

The absorption spectra in PbI_2 bulk thin film and PbI_2/CdI_2 multi quantum wells have been observed under pressure at 77K. The diamond anvil cell with coaxial bellows device was used for applied pressure at low temperature. A silicone oil was used as a pressure medium and the pressure was estimated by a ruby R_1 luminescence line. Figure 1 shows the pressure changes in the exciton transition energies in a PbI_2 thin film and PbI_2/CdI_2 multi quantum wells: in PbI_2/CdI_2 samples PbI_2 and CdI_2 layer are well and barrier layers, respectively. Exciton transition energies of both bulk thin film and multi quantum well shift to lower energy side with increasing pressure. The pressure coefficient of the exciton transition energy in thin film of PbI_2 is obtained to be -105 ± 5mev/GPa. The pressure coefficient in superlattices depends on the well thickness. In the PbI_2/CdI_2 samples with 49 and 42A well thicknesses, the pressure coefficients are obtained to be -93 ± 5meV/GPa and -70 ± 5 meV/GPa, respectively.

In bulk PbI_2 crystals, the pressure shift of exciton transition energy originates from change in valence and conduction band structures under pressure, resulting in the smaller band gap energy. The difference of pressure coefficients of exciton transition energies between bulk PbI_2 thin film and PbI_2/CdI_2 multi quantum wells is due to the increase in energy separation between electron and hole subbands for a decrease in the well width under pressure: this results in the larger exciton transition energy.



Figuer 1. Perssure changes in the exciton transition energies in a PbI_2 thin film and PbI_2/CdI_2 superlattices with well thicknesses of 42A (6 layers) and 49A (7 layers).

GERMANIUM CLUSTERS IN ZEOLITE Y

H. Míguez [1], V. Fornés [1], F. Meseguer [2], F. Márquez [1] and C. López [2].

(1) Instituto de Tecnología Química (UPV-CSIC), Avda de los Naranjos 46022.

Fax: (96) 3877809, e-mail: becitq @ itq.upv.es. Valencia. Spain.

(2) Instituto de Ciencia de Materiales (CSIC), Cantoblanco, 28049, Madrid. Spain

We have developed a new method for obtaining germanium clusters using the porous structure of zeolite Y (Faujasite) as a matrix. Particles so obtained present a high stability and strong quantization effects.

Clusters synthesis. GeO_2 crystallites are formed by hydrolysis of $GeCl_4$ by the water trapped in the faujasite α cavities (diameter: 1.2 nm). Following this, Ge^0 is obtained by reduction of GeO_2 and GeO in H_2 at 470 °C, which apparently is the lowest GeO_2 reduction temperature reported and far below that of bulk GeO_2 (700 °C). Temperature Programmed Reduction (TPR) and XPS techniques are used for monitoring 'in situ' the reduction processes.

Optical properties. Germanium nanoparticles present an absorption edge at 2.2 eV, which is blue shifted by 1.4 eV with respect to the bulk value. A softening (Δv=2 cm^{-1}) and an asymmetric broadening of the germanium Γ_{25}· phonon are also reported. Both results agree with exciton and phonon quantum confinement estimates. If the temperature is increased until the zeolite porous structure ruptures, aggregation occurs. The Raman peak narrows and recovers the bulk frequency value (300.5 cm^{-1}) and the value of the absorption edge is then close to that of the bulk material (0.79 eV).

GERMANIUM CLUSTERS IN ZEOLITE Y

Hernán Míguez. Instituto de Tecnología Química de Valencia (UPV-CSIC).

Avda. de los Naranjos s/n. 46022. Valencia. Spain.

Fax: (96) 3877809. e-mail: becitq @ itq.upv.es

ORAL PRESENTATION

A new method for obtaining Ge nanoparticles has been developed using the porous structure of zeolite Y as a matrix. Samples were obtained by reduction of GeO_2 nanocrystals, previously grown in zeolite α-cages, in H_2 at 470 °C. This is apparently the lowest GeO_2 reduction temperature reported and is probably due to the influence of the host. Temperature Programmed Reduction (TPR) and XPS techniques are used for monitoring 'in situ' the reduction processes. Figure 1 shows three reduction experiments (solid lines) performed at different final temperatures (dashed lines). Peak 1 corresponds to GeO formation from GeO_2 and peak 2 to Ge^0 clusters formation from GeO, as was validated by XPS. As the reduction process evolves, the optical properties of the sample change. The first reduction process (see fig. 1a, GeO formation) does not show either a Raman peak or reflectance in the regions of interest (fig. 2a and 3a). The second reduction process (fig. 1b, Ge^0 clusters formation) presents an absorption edge at 2.2 eV, which is shifted by 1.4 eV with respect to the bulk value (fig. 3b). A softening ($\Delta\nu$=2 cm^{-1}) and an asymmetric broadening of the germanium $\Gamma_{25'}$ phonon are also reported (fig. 2b). Both results agree with exciton and phonon quantum confinement estimates. If the temperature is increased until the zeolite porous structure ruptures (fig. 1c), aggregation occurs. The Raman peak narrows and recovers the bulk frequency value (300.5 cm^{-1}) and the value of the absorption edge is then close to that of the bulk material (0.79 eV) (fig. 2c and 3c). We can estimate an average diameter of 3 nm for the Ge nanocrystals from both Raman and optical absorption results.

TIME-RESOLVED STUDIES OF RESONANCE FLUORESCENCE AND POLARITON PROPAGATION IN GaAs THIN LAYERS

H. Schneider and K. Köhler
Fraunhofer-Institut für Angewandte Festkörperphysik, Tullastrasse 72,
D-79108 Freiburg, Germany
Fax: (+49) 761-5159-359; email: hschneider@iaf.fhg.de

Polariton effects play a fundamental role for the optical properties of bulk semiconductors and multiple quantum wells. These effects become particularly important if there is an optical confinement, which is the case in waveguide structures and microcavities. In GaAs thin layers (a few 100nm thick), polariton splittings are induced by the confinement of the excitonic polarization within the microstructure.

In the present work, we report on the time-resolved photoluminescence (PL) of thin bulk-like GaAs layers, which are excited nearly resonantly at cryogenic temperatures by transform-limited picosecond laser pulses. The PL spectra show clear signatures of polariton effects. Simultaneous excitation of several polariton modes gives rise to structures in the PL time dependence due to polariton interference during the initial 50 ps after the excitation. We also found experimental evidence that the propagation of these modes occurs with different group velocities.

At suitable GaAs thicknesses, the PL signal shows a single polariton-like mode, and a broader line which has the spectrum of the pulsed laser. By varying the excitation wavelength, both components change their intensities in a characteristic way. The behavior can be explained within a forced harmonic oscillator model, where the laser-like spectrum arises from the forced oscillations of the excitons during laser excitation. Within this model, it is also possible to distinguish between the coherent and incoherent contributions to the resonantly excited PL. In GaAs, we thus find that most of the signal is incoherent.

This distinction can be used to gain new information on the physical origin of the emission from resonantly excited excitons, which has been under controversial discussion in the last few years. Since the initial emission is resonant with the laser, it has been explained in terms of resonant Rayleigh scattering [1], which is a coherent process. More recently, the signal has been interpreted as a luminescence from a cold, non-thermalized exciton distribution, which decays mostly due to radiative excitonic recombination and scattering into non-radiative exciton states [2]. Our results indicate that the initial PL signal under resonant excitation in bulk GaAs arises from a cold exciton population, and that the coherent part is very small, typically less than 10%.

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FABRICATION OF CdZnSe/ZnSe-NANOSTRUCTURES BY THERMALLY ASSISTED ELECTRON CYCLOTRON RESONANCE PLASMA ETCHING

T. Kümmell, G. Bacher, A. Forchel, *J. Nürnberger, and *G. Landwehr

Technische Physik, *Experimentelle Physik III, Universität Würzburg, Germany

FAX: +49-931-888-5143 EMAIL: Tilmar.Kuemmell@cip.physik.uni-wuerzburg.de

We have developed a low-damage dry etch technology for the fabrication of II-VI-nanostructures. Thermally assisted electron cyclotron resonance (TA-ECR) plasma etching was used for the lateral patterning of ZnSe-based heterostructures in order to reduce process induced damage compared to common reactive ion etching (RIE) techniques. Wire patterns were defined by electron beam lithography on CdZnSe/ZnSe single quantum wells. The etching process was perfomed in a UHV-chamber using Cl_2 and BCl_3 as reactive gases.

At ion energies of about 40 eV, physical etching characteristics like steep wire sidewalls and smooth surfaces are predominating. By reducing the ion energy to about 3 eV and simultaneously increasing the substrate temperature to about 160°C, the etching mechanism is changed to a purely chemical process. In this case, we obtain typical etch rates of about 20nm/min.. The scanning electron microscope characterization reveals a substantial underetching of the Ti masks allowing the realization of wires with a lateral size of 18 nm. Additionally, the etching profile depends strongly on the wire orientation. While for wires parallel to the [01-1] direction a triangular etching profile is observed, vertical sidewalls are obtained for wires oriented parallel to the [011]-direction. These features indicate the prevailing chemical character of the reactive etch process.

Using photoluminescence (PL) spectroscopy the quantum efficiencies of TA-ECR-etched and RIE-etched wires were investigated. For 60 nm wires the PL intensity is enhanced by one order of magnitude compared to structures fabricated with a standard low damage Ar-BCl_3-RIE-process. We obtained clear PL-signals from 35 nm wide wires, whereas wires patterned by the RIE process are optically inactive below 50 nm. Thus, TA-ECR plasma etching, which may be applied to a variety of material systems, provides a promising new technology for the fabrication of ultranarrow, optically active nanostructures.

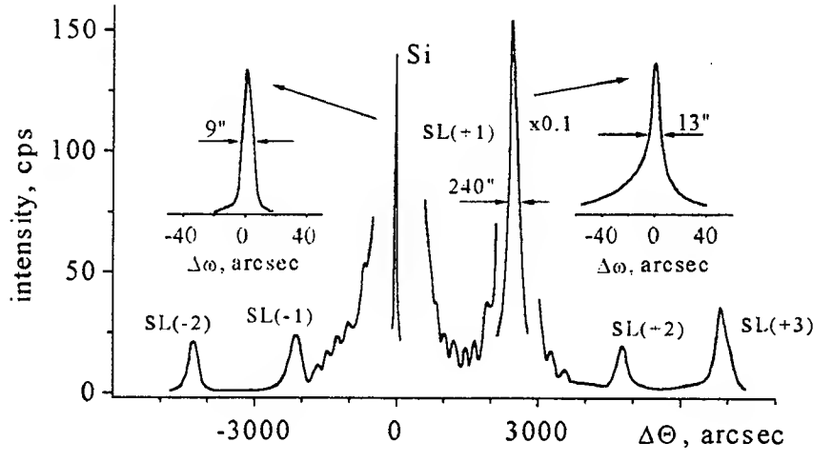
Molecular Beam Epitaxy-Grown CdF_2-CaF_2 Superlattices on Si(111)

A.Yu. Khilko, S.V. Gastev, R.N. Kyutt and N.S. Sokolov

Ioffe Physico-Tecnical Institute, Russian Academy of Sciences, 194021 St.Petersburg, Russia

Among II group fluorides, CdF_2 attracts especial attention because of its unusual properties. It combines wide bandgap (8eV) with existense of shallow (0.1 eV) donor states. Possibility of growing high-crystalline quality CdF_2 layers on CaF_2/Si(111) has been recently demonstrated [1]. Taking into account 3eV band offset at CdF_2/CaF_2 interface [2] and close lattice matching of CdF_2 and CaF_2 to Si, one can expect attractive electronic properties from CdF_2-CaF_2 superlattices (SLs).

In this work, CdF_2-CaF_2 SLs were grown on Si(111) with total thickness up to 100 nm and periodicity from 2 to 20 nm. The structures grown were characterized by double and triple crystal X-ray diffractometry in both symmetrical Bragg and transmittion Laue geometry, and impurity photoluminescence (PL) probe technique [1]. The Figure shows Θ-2Θ and ω-scanning rocking curves obtained in Bragg geometry from a SL with 6.9 nm period. Very narrow ω-scan curve indicates that the SL is pseudomorphic and has high structural perfection. Its coherence with Si substrate was independently confirmed by PL measurements. For larger period (T>15 nm) stress relaxation was observed. Distinct satellites caused by periodic variation of the structure factor across SL were revealed on the ω-scan curves obtained in Laue geometry.



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OPTICAL PROPERTIES OF Se AND HgI_2 CHAINS ISOLATED IN CHANNELS of $AlPO_4$-5 SINGLE CRYSTAL

Zi Kang TANG, Michael M. T. LOY, Jiesheng CHEN* and Ruren XU*

Physics Department, Hong Kong University of Science and Technology

Clear Water Bay, Kowloon, Hong Kong

* *Department of Chemistry, Jilin University, 119 Jiefang Road, Changchun 130023, China*

Se and HgI_2 were successfully introduced into the one-dimensional channels of $AlPO_4$-5 single crystal by vapor defusion method. The channels with diameter of 7.3 Å are parallelly packed in a hexagonal structure. The samples behave like good polarizers with high absorptions for the polarization of the light parallel to the chains (E//C) and with high transparency for E⊥C. The absorption bands are found to be shifted towards high energy about 0.6 eV for the Se chain and 1.4 eV for the HgI_2 chain from the band edge transitions of *t*-Se crystal and bulk HgI_2 exciton transition, respectively, which is attributed to the quantum size effect on the excitation energy in a quantum wire. The small blue shift for Se chain is due to the initial chain-character in *t*-Se, while the large blue shift for HgI_2 chain results from the strong confinement of Wannier exciton. Quantitatively, however, the experimental result largely deviates from the calculation based on the effective mass approximation. The electron-hole pair in such a thin wire seems to behave a particle with the bare electron mass.

EFFECTS OF INTERNAL STRAINS ON RESONANT TUNNELING OF HOLES

A. C. BITTENCOURT, A. M. COHEN
Departamento de Física, Universidade do Amazonas, 69077-000 Manaus - AM - Brazil.
and
G. E. MARQUES
Departamento de Física, Universidade Federal de São Carlos,13565-905 - São Carlos - SP - Brazil,

The considerable interest in resonant tunneling of carriers lie in their applications to electronic devices such as oscillators operating in high frequency regime. We made an detailed theoretical study of the effects of internal strains on mixing of resonant hole states in double-barrier structures submitted to different strains. We shown that the tunneling probability of holes, for two $Ga_xIn_{1-x}As$-InP(compression and extension) and one lattice-matched $Ga_yIn_{1-y}As$-InP (no strain) samples, are drastically affect by the type of axial strain imposed by lattice mismatch. Figure below shows clearly how one can used internal strains to improve the performance and the quality of an electronic device.

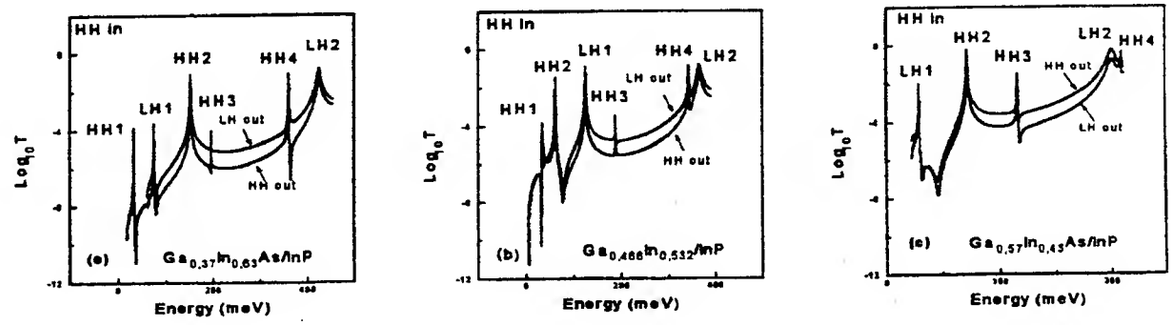

Figure 1:

ELECTRONIC STRUCTURES OF p-TYPE δ-DOPED SEMICONDUCTORS UNDER IN-PLANE MAGNETIC FIELD

G. E. Marques, G. -Q. Hai, N. Studart

Departamento de Física, Universidade Federal de São Carlos, 13565-905 São Carlos, SP, Brazil

and

A. M. Cohen

Departamento de Física, Universidade do Amazonas, 69068-900 Manaus, AM, Brazil

In recent years, there has been considerable interest in δ-doped semiconductor structures due to their possible applications to electronic and photonic devices. With ultrafine control for profiles it is possible to create single monolayers of p-type(Be) and n-type(Si) dopants in GaAs[1] which confine holes and electrons respectively. In these structures, typically there are several subbands populated. In this work, we have made a detailed theoretical study of the electronic structures of a p-type δ-doped semiconductor under the application of an in-plane magnetic field.

The electronic hole states are determined by solving the Luttinger-Kohn Hamiltonian model[2] for valence band carriers in the presence of the self-consistent confining potential, for a given total density n(z) due to all populated light and heavy hole states, as determined from the Poisson's equation. Exchange and correlation effects are considered within the local density approximation. We discuss the details of the effects of the in-plane magnetic field on the energy dispersions of the hole Landau levels and the subband populations. Our calculation shows that the coupling between hole states is strongly affected by the in-plane magnetic field.

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Theoretical and experimental studies of ion-implanted 3D–0D–3D semiconductor structures: I–V characteristics, shape of the zero dimensional fine features and direct investigation of quantum dot wave functions

M. Boero, G. Faini*, C. Vieu*, F. Laruelle*, H. Launois*, J.C. Inkson

Dept. of Physics, University of Exeter, Stocker Road, Exeter, EX4 4QL, UK

*L2M-CNRS, 96 Avenue H. Ravera, BP107, Bagneux Cedex, 92225–France

Transport properties of zero-dimensional structures have been extensively studied and have proved a valuable technique to obtained information on the spectra of quantum dots. Here we report on theoretical investigations of transport properties of quantum dots fabricated by means of a ion-implantation technique. In this kind of devices the quantum dots are sandwiched between two bulk 3D contacts. In these structures transport occurs in the resonant tunnelling regime. However, since the contacts are not laterally confined while the dot is, tunnelling occurs without conservation of lateral state. This fact poses new challenges from the theoretical viewpoint because one has to understand the coupling between each dot level and all the states in the contacts to correctly model such structures. In order To do so we have adopted anon-equilibrium Green's function technique which allows us to calculate the current flowing through each dot state for a given applied bias. The effects of the electrostatic interaction inside the dot are included by using a Hubbard-Hamiltonian. We have calculated the I–V characteristics for such structures and we have found good overall agreement with the experiments. In particular we remark upon the different current amplitude arising from different dot states. Such effects are confirmed experimentally and open the way to obtain direct information on the actual electronic wave functions in a quantum dot . The effect of a magnetic field is also discussed.

MAGNETOSPECTROSCOPY OF INP/ALINP MULTI-QUANTUM WELLS

R.W. Martin*, J. Lammasniemi†, K. Tappura†, and K. Smekalin†.

*Department of Physics and Applied Physics, Strathclyde University, John Anderson Building, 107 Rottenrow, Glasgow, G4 ONG.

†Department of Physics, Tampere University of Technology, P.O. Box 692, FIN-33101 Tampere, Finland.

Measurements of absorption and photoluminescence on an InP/$Al_{0.2}In_{0.8}P$ multi-quantum well in high magnetic fields provide extensive details of the band-structure and properties of a rarely studied material combination. Three excitonic transitions are resolved at zero field and compared with calculations of the confined energy levels using an envelope function approach. The heavy and light holes are shown to have type I and type II band line-ups, respectively, and estimates of the heterojunction band offsets can be made ((325±10)meV for the conduction band). On applying magnetic field numerous Landau level transitions are resolved, arising from both the lowest heavy-hole exciton (e1-hh1) and from a parity forbidden light hole transition (e1-lh2). Calculations of the Landau level energies using a variational hydrogenic model, taking into account effects of strain and non-parabolicity, enable estimates of the in-plane hole masses and binding energies in both cases.

Measurements of the photoluminescence as a function of both temperature and laser intensity will be described. The emission peaks due to the e1-hh1 and e1-lh2 transitions are both shifted by approximately 10meV on decreasing the power of the 488nm laser line from 100mW to 1mW. On cooling the structure below 30K up to four additional emission peaks are resolved at energies below the light hole exciton, providing information concerning the phonon properties of the material.

ThB Coherent transport in quantum structures

Using Quantum Interference to Control Semiconductor Photocurrents

P. B. Corkum, E. Dupont, H. C. Liu, E. Constant and H. Stapelfeldt

National Research Council of Canada
Ottawa, Ont. Canada

Modern semiconductor physics shares many phenomena with atomic and molecular physics. Quantum wells are somewhat like atoms and multiple quantum wells are similar to molecules. We describe an experiment that is the semiconductor analogue of a recent atomic physics experiment [1].

Using a superposition of a laser beam and its second harmonic, we demonstrate that both the magnitude and the direction of a photocurrent can be determined by the relative phase of the beams in an unbiased quantum well device. To do this, an electron is produced in the continuum by means of either a single photon transition producing an asymmetric continuum wave function or a two photon transition producing a symmetric continuum wave function. If the coherent superposition of these electron wave functions destructively interfere in one direction, then they must constructively interfere in the other, implying a current flow in that direction. The relative phase of the light determines the relative phase of the electron wave functions and therefore, their direction.

We conclude with a second example of the strong connection between atomic, molecular and solid state physics. Researchers have predicted the destruction of tunnelling in intense, time dependent fields in double quantum well structures [2]. Double well potentials occur both in solid state structures and in molecular ions. In molecular ions the destruction of tunnelling is responsible for a new and very efficient ionization pathway for intense field ionization [3]. This pathway is predicted to lead to a large increase in the ionization rate at a critical internuclear separation at which tunnelling is just being destroyed. We use the flexibility that we have with molecules to vary the internuclear separation showing the peak in the ionization rate occurring in the region where electron tunnelling is destroyed.

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Antiresonant hopping phenomena in a 1D superlattice

A.Nogaret, L.Eaves, P.C.Main, T.J.Foster, M.Henini, G.Hill#
Dept.of Physics, University of Nottingham, Nottingham NG7 2RD, UK
 # Dept. of Electrical Engineering, University of Sheffield, Sheffield S1 3JD, UK

We investigate the scattering mechanism responsible for the hopping current in the Wannier-Stark regime of a 20 period GaAs-10.2nm/AlAs-1.3nm superlattice. In the presence of a quantizing magnetic field applied perpendicular to the layers, hopping occurs between the partially filled Landau levels of the same index which form a cascade of quantum boxes, fig.1. Conduction through the ground miniband produces the negative differential resistance at V=0.35 V while elastic scattering transitions involving a change in the Landau level index are responsible for current satellites at higher bias, e.g. $\Delta n=1$ in fig.1. The transition from the ground to the first electric subband takes place at V=1.7V in agreement with the calculated band structure.

After the resonant peak the hopping conductance shows oscillations as a function of bias, arrowed in fig.1. These appear independent of the magnetic field and are reproduced in all samples investigated. Their period, ≈45 mV, scales well with that of the predicted [1] oscillations due to the opening of energy gaps in the folded dispersion curve of acoustic phonons, $20\times(2\pi hs/d)\approx 32$ mV, where s is the sound velocity in GaAs and d the period of the superlattice. By inhibiting in-plane scattering, the magnetic field enhances electron coupling to 1D lattice vibrations. We thus ascribe the antiresonances to phonon gaps and use this technique to probe the phonon band.

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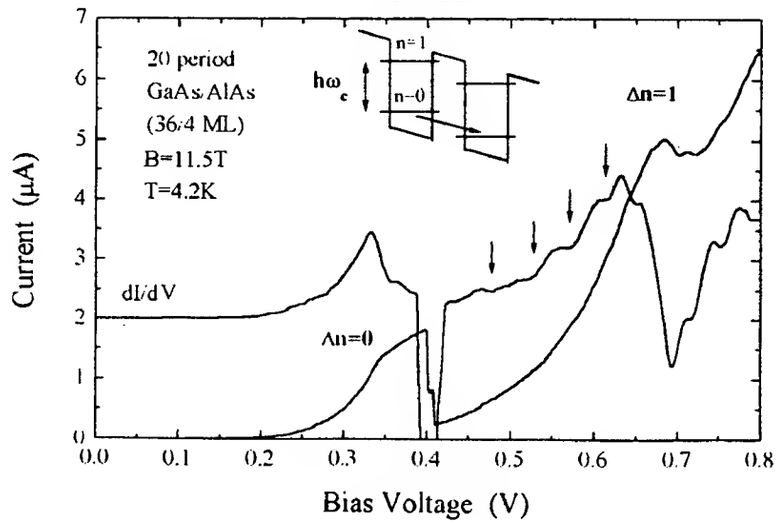
Figure 1



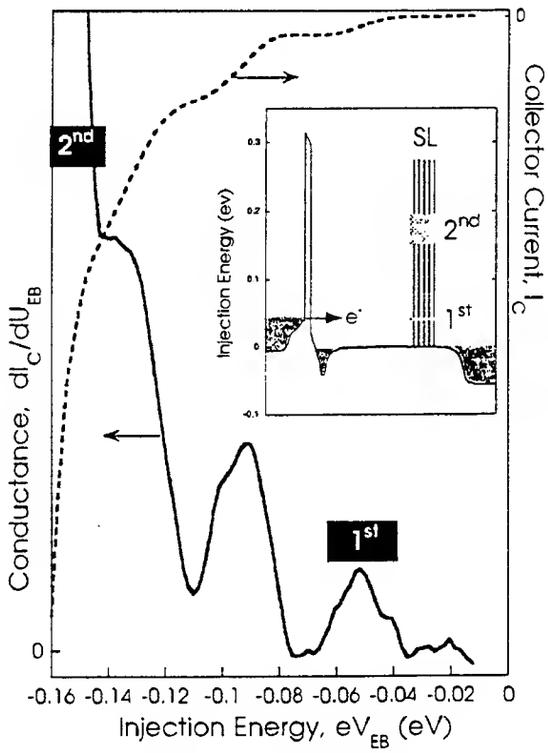
DIRECT BALLISTIC ELECTRON SPECTROSCOPY OF VERTICAL SUPERLATTICE MINIBANDS

C. Rauch, G. Strasser, K. Unterrainer, W. Boxleitner, E. Gornik
Solid State Electronics, TU Vienna, Floragasse 7, A-1040 Vienna, Austria
B. Brill, U. Meirav, M. Heiblum
The Braun Center for Submicron Research, Weizmann Institute of Science, Rehovot 76100, Israel

We present direct evidence of ballistic electrons traversing a nominally undoped GaAs/AlGaAs superlattice consisting of 5 periods of a 8.5nm GaAs well and 2.5nm $Al_{0.3}Ga_{0.7}As$ barrier.

The measurements are carried out using a hot-electron transistor pioneered by Heiblum et al.[1] as an electron energy spectrometer. A tunable electron beam with an energy distribution of about 8meV is generated by a tunneling emitter, traverses a thin (12nm) highly doped GaAs region (base), passes an undoped region and the superlattice to be finally collected and energy analyzed.

The measured collector current (I_c) as a function of the emitter-base bias at 4.2K is shown in the figure. The derivative of I_c with respect to V_{EB} is proportional to the number of ballistic electrons in an energy unit passing through the superlattice minibands[2,3]. The peak in the conductance between 40meV and 60 meV corresponds to the first miniband. Longitudinal optical (LO) phonon replica are observed at energies of about 90meV and 130meV which are ascribed to single and double LO phonon emission processes. The sharp increase at 140meV corresponds to the lower edge of the second miniband. The miniband positions are calculated using a fully self-consistent Poisson-Schrödinger calculation. We calculate that the first miniband starts at 39meV above the GaAs conduction band edge and extends up to 54meV. The second miniband ranges from 144meV to 203meV. From our experimental data we extract the miniband gap to be 80meV in good agreement with the calculations. This is the first experimental analyzing of a nominally field free superlattice. In addition we study the transfer ratio dI_C/dI_E which gives a measure of the ratio of electrons traveling ballistically through the superlattice. We intend to resolve the discrete Wannier Stark states by using a resonant tunneling diode as an injector.



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MICROSTRIP STABILIZED SEMICONDUCTOR ASYMMETRICAL QUANTUM WELL STRUCTURE GENERATOR FOR MILLIMETER AND SUBMILLIMETER WAVELENGTH RANGE

A.A. Belousheкin, A.S. Ignatyev, A.L. Karuzskii, V.N. Murzin, A.V. Perestoronin, A.M. Tskhovrebov
P.N. Lebedev Physical Institute, Leninsky prosp. 53, Moscow 117924, Russia

The results of theoretical and experimental investigation of vertical transport and high frequency oscillatory properties of double-barrier and tripple-barrier resonant tunneling stuctures (DBRTS and TBRTS) in combination with a microstrip resonator stabilizing circuit are presented. The numerical simulation data are obtained revealing the higher efficiency of a tripple-barrier structure compared with a double-barrier one since the peak current value J_p for the TBRTS may be significantly higher of the J_p for the DBRTS at the same peak-to-valley current ratio J_p/J_v due to sufficient broadening of the electronic transparency range, that is rather prominent to achieve higher power level and discernible oscillations at higher frequencies.

For the first time the implementation of a resonant tunneling GaAs/AlAs quantum-well generator stabilized by use of the normal and superconducting microstrip resonator are presented, which are rather encouraging for millimeter and submillimeter wavelength applications. The asymmetrical multiple quantum well structures include the undoped spacer layers, inserted between heavily doped electrodes and tunneling barriers, which prevent the incorporation of segregated impurities into the active part of the structure during epitaxial growth and improve the frequency responce of a device.The system of coplanar contacts used provides the extremely low *RC* time delay in the negative-differential conduction (NDC) region of the current-voltage (*I-V*) curve due to a decrease in the capacitance and the series resistance of a device. The asymmetrical quantum well resonant tunneling structures are investigated in combination with the microstrip resonator configuration providing a best circuit conditions for realization of high frequency (up to THz band) oscillations by use of planar active structures. To reduce the attenuation and distortion of pulses and to increase the quality-factor of microstrip system, the dispersion-loss relations of microstrips are taken into account. The proper tuning of intermode coupling is shown to increase significantly a quality-factor value of the resonator (from $<10^3$ up to 10^6 for 10 GHz linear Nb microstrip resonator).

Microwave oscillations have been found at frequencies around 1 GHz with a power level of 10^{-4}-10^{-5} W from GaAs/AlAs DBRTS stabilized by a microstrip resonator for the first time. The *I-V* characteristic of measured DBRTS shows rather high values of a Jp/J_v ratio around 4.3 (77 K) and 2 (300 K) and of a peak current density around 2.2×10^4 A cm^{-2} (77 K) and 1.9×10^4 A cm^{-2} (300 K). The discontinuous nature, hysteresis and instability of the expermental *I-V* curve in the NDC region were observed that appear to be caused by the bistability due to effects of the space charge in quantum well and especially in coplanar contact regions. The nonlinear dynamical characteristics, current bistabilty, modulation phenomena in microwave oscillations under the conditions of self-excitation in a back-loop circuit are investigated. The dynamic hysteresis and strong modulation phenomena which have been observed manifest the use of multiple quantum well-barrier resonant tunneling structures in narrowband as well as in broadband pulsed mm and submm applications.

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ThC Terahertz phenomena and Bloch oscillations

Observation of Shapiro steps and direct evidence of Bloch oscillations in semiconductor superlattices

K. Unterrainer[+], B.J. Keay, M.C. Wanke, S.J. Allen,

D. Leonard, G. Medeiros-Ribeiro, U.Bhattacharya, M.J.W. Rodwell

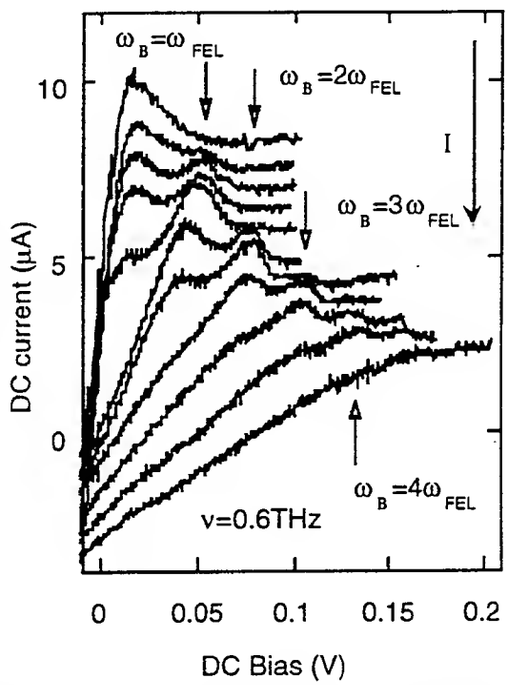
Center for Free -Electron Laser Studies and Materials Department, University of California, Santa Barbara, CA 93106

+) Institute for Solid State Electronics, Technical University Vienna, A-1040 Vienna, Austria

Bloch oscillation is a well defined normal mode of a semiconductor superlattice at THz frequencies, when $w_B \cdot \tau > 1$. The first observation of Bloch oscillations was made in a degenerate four wave mixing experiment /1/ and in a transient THz emission experiment of optical excited electrons /2/. Continuous Bloch emission of electrically injected carriers in a superlattice has not yet been observed.

In our work we have combined transport and THz spectroscopy to show that DC current driven Bloch oscillation couples to external radiation. We used superlattice structures with a lowest miniband width of 20 meV.

The influence of an external THz electric field from the UCSB free electron laser on the superlattice current is shown in the figure /3/. We have observed resonant changes in the current-voltage characteristics when the Bloch frequency is resonant with an external laser field and its harmonics. The resonance consists of a peak in the current which grows with increasing laser intensity accompanied by a decrease of the current at the low bias side. When the intensity is increased further the first peak starts to decrease and a second peak appears. At the highest intensities we observe up to a four photon resonance. We also find an onset for AC localization /4/. Our results show clearly that the external radiation couples to Bloch oscillations, contrary to theoretical suggestions that THz radiation would not couple to a uniform Wannier Stark ladder. The effect is an analogy to Shapiro steps in S-I-S junctions that support the AC Josephson effect.



From the frequency dependence we can extract a miniband scattering time which is compared to the scattering time obtained from transport measurements. From the value of the photo current we can determine the power transfer into the photon field. We estimate a negative THz conductance of our superlattice mesa which is compared to theoretical models. The experiment demonstrates that a superlattice is a possible gain medium for THz oscillators. We acknowledge financial support by the Office of Naval Research, ARO, NSF, AFOSR and by the Austrian Science foundation.

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TRANSITION FROM CLASSICAL TO QUANTUM DYNAMICS IN SUPERLATTICES IN INTENSE THZ ELECTRICAL FIELDS

S. Zeuner[1], B.J. Keay[1], S.J. Allen[1], K.D. Maranowski[2], A.C. Gossard[2], U. Bhattacharya[3], and M.J.W. Rodwell[3]

[1] *Center for Free-electron Laser Studies, UC Santa Barbara, CA 93106,*
[2] *Materials Department, UC Santa Barbara,*
[3] *Department of Electrical and Computer Engineering, UC Santa Barbara.*

We have investigated the THz-response of a series of GaAs/$Al_xGa_{1-x}As$ superlattices ranging from the sequential tunneling limit to superlattices with a miniband width of 10 meV. In the sequential resonant tunneling case we observe a transition from classical rectification at frequencies below 600 GHz to quantum response above 1 THz. In the quantum regime, the current-voltage characteristics show distinct peaks due to absorption and stimulated emission of up to three THz-photons. At high THz field strengths ($\sim$ 10 kV/cm) the photon-assisted channels dominate the transport, leading to dynamic localisation, absolute negative conductance, and, perhaps more important, gain just below the Stark splitting of the quantum well ground-states.

We obtain quantitative agreement of these observations with Tucker's theory of PAT by invoking the concept of the "instantaneous" I-V of the superlattice. The dc I-V curves are complicated by charge buildup in the wells and the formation of a high field domain. But these relatively slow processes cannot take place on the timescale of the oscillating THz field. As a result, measuring the I-Vs in sufficently strong THz fields turns out to be a powerful tool to reveal the underlying, instantaneous current-voltage characteristics, free of domain formation.

The absorption and stimulated emission of THz photons in these superlattices is especially important since it establishes a process that may lead to solid state THz sources and detectors. Although we measure dc transport, we can extract a measure of the gain. At those levels of the THz radiation, where direct tunneling is completely suppressed, each electron in the current has to emit a photon to be able to tunnel to the adjacent well, so that this current measures the THz gain. Although the theory of PAT is believed to be valid only in the sequential tunneling limit, we found the features associated with PAT to persist even for superlattices with a relatively wide miniband of Δ = 10 meV. As the current density of these devices increases with the miniband width, we find the gain in the Δ = 10 meV sample to be already $\sim$ 50 times higher than in the sequential tunneling superlattices.

THz emission from a narrow-band superlattice - experimental evidence for the shortcomings of the Bloch Equation method

F. Wolter, P. Haring Bolivar, A. Müller, H.G. Roskos, K. Köhler*, and H. Kurz

Institut für Halbleitertechnik II, RWTH Aachen, Sommerfeldstr., D-52056 Aachen, Germany
*Fraunhofer-Institut für Angewandte Festkörperphysik, D-79108 Freiburg, Germany

The Semiconductor Bloch Equations (SBE) have been successfully employed for the microscopic description of coherent optical excitations in semiconductors taking into account Coulomb interaction. Despite its wide acceptance and elaborate extensions, the model is fundamentally problematic because of its artificial reduction of the dynamics to only three types of observables (electron densities, hole densities and polarizations) without comprising systematic truncation criteria. Therefore an alternative model, the dynamics controlled truncation (DCT)[1] was derived. It describes within a different hierarchical set of density matrices the dynamics of the system up to a given order of the electromagnetic field and in contrast to the SBE this model incorporates mathematically exact truncation concepts. In this contribution we present a special experimental approach proposed in [2] which allows to compare both theoretical models. According to the SBE [2] the THz emision is not influenced by Coulomb interaction (after dephasing of the interband polarization), while the DCT [3] model predicts that the emission is strongly influenced by it. We report on THz emission measurements on a narrow-band $GaAs/Al_{.35}Ga_{.65}As$ superlattice selectively excited at its lower edge where the effects of the Coulomb interaction are particularly conspicuous. The dependence of the measured THz-frequency on the electric bias field shows a hyperbolic dependence with a minimum oscillation frequency of 0.75 THz. This completely disagrees with the predictions of the SBE where a linear dependence is expected due to the continuous fan out of the Wannier Stark Ladder states. Instead, the hyperbolic dependence of the THz emission is characteristic for an anticrossing of the involved states. A comparison with transmission experiments allows to identify this anticrossing as being due to the avoided crossing of the miniband exciton with the Wannier-Stark transitions. This therefore confirms the DCT prediction that THz emission is dominated by the Coulomb interaction, underlining the shortcomings of the SBE method.

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OPTICAL PHONON MODES AND POTENTIALS IN PERIODIC QUANTUM DOTS

Bang-fen Zhu

National Laboratory of Superlattices and Related Microstructures

Institute of Semiconductors, Chinese Academy of Sciences.

P. O. Box 912 Beijing 100083, China

(Fax: 86-10-2562389; Email: bfzhu@red.semi.ac.cn)

By extending the optical phonon model in quantum wells and quantum wires[1] to the periodically arranged quantum dots, the dispersion relation , the optical displacements and the associate electrostatic potentials of the optical phonon modes in zero-dimensional systems are presented. The characters for each type of modes, such as the LO- and TO- bulklike modes, the interface like modes, are illustrated with special attention paid to the roles played by the finite bulk phonon dispersion. In addition to the dots arranged according to the simple cubic periodicity, the phonon modes and potentials in several other specially-designed quantum dot structures, e.g. the anti-dots structure, the f.c.c. structure, the b.c.c structure, etc. will be presented and discussed. The differences between the energy loss rates in quantum dots evaluated with the realistic phonon modes and that deduced from the 3-Dimensional phonon mode are discussed.

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Nuclear spin-lattice relaxation in superlattices

A. Shik
A.F.Ioffe Physical-Technical Institute, 194021 St-Petersburg, Russia;
I.D.Vagner
Grenoble High Magnetic Field Laboratory MPI-FKP and CNRS
BP 166, 38042 Grenoble Cedex 09, France

The nuclear spin-lattice relaxation rate in a superlattice subjected to a strong magnetic field **B** parallel to its axis is studied theoretically. The relaxation rate T_1^{-1} is shown not to be described by the well-known Korringa formula but to exhibit a dramatic magnetic field dependence. The energy conservation law allows flip-flop spin reversal processes due to the hyperfine interaction between the nuclear and electron spins only in some intervals of **B**. In particular, the width of the highest occupied superlattice subband Δ must exceed the spin splitting of Landau levels which results in the relaxation offset at some critical magnetic field B_c. At $B < B_c$ the relaxation rate T_1^{-1} vs B dependence has giant oscillations depending on the sample doping (that is on the Fermi level position).

Typically the Landau level separation $\hbar\omega_c$ exceeds considerably their spin splitting $g\mu_B B$ (μ_B is the Bohr magneton, g is the electron g-factor) and relaxation processes are determined by electron transitions between spin sublevels of the same Landau level. However, the situation can be changed by the tilting of magnetic field decreasing $\hbar\omega_c$ at a constant $g\mu_B B$. At some critical tilt angle these two quantities become equal and inter-Landau-level processes come into action which changes noticeably the T_1^{-1} vs B dependence.

RAMAN STUDY OF INTERFACE ARRANGEMENT IN GaAs/AlAs SUPERLATTICES GROWN IN DIFFERENT CRYSTAL DIRECTIONS

*S.W. da Silva, Yu.A.Pusep, J.C.Galzerani, *D.I.Lubyshev, *P.P.González-Borrero, and *P.Basmaji

Departamento de Física, Universidade Federal de São Carlos, C.P.676, 13565-905 São Carlos, SP,Brazil,

**Instituto de Física de São Carlos, Universidade de São Paulo, 13560-970, São Carlos, SP, Brazil*

The optical phonons have been studied by Raman scattering in ultrathin-layer GaAs/AlAs superlattices (SL's) with thicknesses of both layers of a few monolayers. All the samples were simultaneously grown by molecular-beam epitaxy at T=620C in different crystal directions lying in the $(1\ \bar{1}0)$ plane - from the [001] direction to the [110] one. Growth was made without interruptions at the interfaces.

In all the SL's we observed the confined optical modes in the frequency range of the GaAs optical phonons; the analysis of their frequency positions allowed us to study the interface roughnesses. The results gave evidence of the formation of different interfaces depending on the growth direction. The strongest influence of the interdiffusion was found for directions lying between the [001] and [110] axes, while the SL's grown along these two directions reveal relatively weak broadening of interfaces.

In addition, in the (113) oriented SL the splitting of the confined optical modes was found which we assign to the optical phonons confined in the narrow and in the wide parts of the corrugated layers. The value of the observed splitting gave us a possibility to estimate that the corrugation is two monolayers high.

Based on the obtained results we discuss the formation of the interface broadening and come to the conclusion that the different microfaceting in different crystal directions can be a good candidate to explain the observed interface roughnesses. The most pronounced microfaceting resulting in the periodical corrugation of interfaces was observed in the (113) oriented SL.

Well Width Dependence of Interface Roughness Scattering in $GaAs/Ga_{1-x}Al_x$ As Quantum Wells

R. Gupta*, N. Balkan*, M. Cankurtaran**, H. Celik**, A. Bayrakli**, E. Tiras**

* University of Essex, Department of Physics, Colchester, UK

** Hacettepe University, Department of Physics, Beytepe, Ankara, Turkey

Well width dependence of the quantum and the transport mobilities of electrons in $GaAs/Ga_{1-x}Al_xAs$ multiple quantum wells is studied for a range of quantum wells between 50Å and 145Å. Experimental results are obtained from the amplitude analysis of the Shubnikov-de Haas (SdH) oscillations and from the conventional Hall measurements at temperatures between T=1.5K and 4.2K. Theoretical modelling, based on the interface roughness scattering has been carried out for a range of monolayer fluctuation size (Δ) and width (Λ) as to obtain the best fit to the experimental results on individual samples.

Our results indicate strongly that;

i. Interface roughness scattering limits equally both the quantum and the transport mobility,

ii. The nature (small or large angle) and the degree of scattering by interface roughness depend not only on the size and the width of the fluctuations but also on the distribution of these fluctuations within the samples hence;

iii. Unlike the predictions of theoretical models, there is no clearly defined well- width dependence of interface roughness scattering even in samples grown under the same conditions and with identical carrier densities.

RADIATIVE DAMPING OF COLLECTIVE EXCITATIONS IN PERIODIC ARRAYS OF QUANTUM WIRES AND DOTS

S. A. Mikhailov

Institute of Radioengineering and Electronics of RAS, Fryazino, Moscow region 141120, Russia, and Institut für Theoretische Physik, Universität Regensburg, D-93040, Regensburg, Germany

The spectra of collective excitations in low-dimensional electron systems such as quantum wires, quantum dots, antidots, rings were calculated till now neglecting the retardation effects. As far as *the frequency* of collective excitations is concerned, this is justified as retardation effects are determined by the parameter $(a/\lambda)^2$ which is several orders of magnitude smaller than unity in real systems (here a is the period of the structure, $\lambda = c/\omega\sqrt{\varepsilon}$ and c are the wavelength and the speed of light, ε is the dielectric constant of surrounding medium). We show, however, that an influence of retardation effects on *the damping* of collective modes is determined by another parameter, $2\pi f\sigma / c\sqrt{\varepsilon}$, which can be of order unity in structures with high electron mobility (f is the area filling factor and σ is the static conductivity of 2D electrons).

We obtain the analytic solution of the problem of electromagnetic response of a periodic structure of parabolically confined quantum wires (and quantum dots) in a perpendicular magnetic field. We calculate the FIR absorption spectrum and the spectrum of collective excitations *with account* of retardation effects and inter-wire (inter-dot) interaction. It turns out that the radiative damping gives the considerable contribution to the full linewidth of collective modes: it exceeds the damping by collisions if the mobility of electrons is larger than $\sim 3\times 10^5$ cm^2/Vs (assuming the typical parameters of real structures: $f \sim 0.5$ and average 2D electron density is $\sim 5\times 10^{11}$ cm^{-2}).

Growth simulation and optical spectra of quantum wells

F. Große and R. Zimmermann
MPG-AG "Halbleitertheorie"
Hausvogteiplatz 5-7, D-10117 Berlin
e-mail: fg@semic.ag-berlin.mpg.de

Quantum wells (QW) are grown in molecular beam epitaxy (MBE) routinely. But not much is known about the underlying microscopic growth process and its influence on the final QW structure, which determines directly the optical spectra. Here we present an advanced calculation beginning from growth process simulation to the calculation of optical properties including exciton effects.

Concentrating on GaAs/AlGaAs-QW's, it is the position of the Al atoms which contains the entire structural information. Therefore we are led to include the interface roughness as well as the alloy disorder on the same footing.

The MBE growth process is simulated by a Monte-Carlo method using the real crystal structure of the group III elements, improving over known growth simulations on a simple cubic lattice. The used kinetic coefficients are comparable with coefficients deduced from experiment and density functional calculations.

The optical density proportional to absorption is calculated using the simulated structures. Starting with the confinement wave functions for electron and hole of the laterally averaged quantum well the remaining four-dimensional Schrödinger equation for the excitonic polarization is solved without the seperation into relative and center-of-mass motion. Small QW disorder leads to a broadening of the exciton eigenstates, whereas a larger one (potential flucuations exceeding the exciton binding energy) destroys the exciton. In this way, the quantitative disorder influence on the optical QW spectra is studied from lower eigenstates up to the electron-hole continuum.

Magnetic field effects on impurity states in quantum dots

Francisco A.P. Osório

Universidade Federal de Goiás

74001-970 Goiânia - GO - BRAZIL

Oscar Hipólito

Departamento de Física e Ciência dos Materiais,

Instituto de Física de São Carlos, Universidade de São Paulo

Cx.P.: 369, 13560-970 São Carlos, SP, Brazil

François M. Peeters

Department of Physics, University of Antwerp (U.I.A.),

B-2610 Antwerpen, Belgium

A calculation of the electronic ground and excited levels and the corresponding binding energies associated with a shallow impurity placed at the center of a circular quantum dot is performed in the presence of a perpendicular magnetic field. The variational method is used to obtain the energies as a function of the radius of the dot, the strength of the field and the height of the confinement potential barrier. In the absence of the magnetic field the electron wave functions are analytically obtained and the energy levels are numerically determined. The interplay between the confinement and the magnetic field on the binding energies is investigated. It is found that the effects of the magnetic field become more pronounced with increasing the radius of the quantum dot and/or decreasing the height of the potential barrier but there is almost no effect when the magnetic length is larger than the radius of the dot.

Subbands, exchange and correlation effects on collective excitations in parabolic quantum well wires

Antonio Newton Borges

Universidade Federal de Goiás and Universidade Católica de Goiás

74001-970 Goiânia - GO - Brazil

Oscar Hipólito and Salviano A. Leão

Departamento de Física e Ciência dos Materiais,

Instituto de Física de São Carlos, Universidade de São Paulo

Cx.P.: 369, 13560-970 São Carlos, SP, Brazil

The plasmon collective excitations in quasi-one-dimensional (Q1D) quantum-well wires are calculated for two and three-subbands model by using the self-consistent-field approximation theory proposed by Singwi, Tosi, Land and Sjölander (STLS) for the response function of the electron system. The present calculations are applied to GaAs-GaAlAs parabolic quantum-well-wires with the appropriate form factors which take into account the influence of the width of the electron layer. Quantities such as the effective potential, the static structure factor, the pair-correlation function and the plasmon dispersion relation are calculated as a function of energy difference between subbands and electron density. We found that exchange and correlation effects may be quantitatively significant for Q1D electron gas with parabolic confinement potential. In the case where more than one subband is occupied, we found an additional plasmon like intersubband mode. We also found significant differences due to the presence of the local-field correction included in our model calculation when compared to the corresponding RPA results.

The Study of the Quantum Hall Effect in Type II Semiconductor superlattices

M.Singh and S.Kuzmin
Department of Physics, University of Western Ontario
London, Ontario, Canada N6A 3K7

The recent experimental study of the Quantum Hall Effect (QHE) in type II semiconductor superlattices shows a very interesting and complicated behaviour of the Hall conductivity[1].In particularly, an intriguing possibility is that Hall resistance can suddenly drop while the magnetic field strength is increasing. In type II superlattices such as GaSb/InAs, two dimensional electrons and two dimensional holes are confinrd in InAs and GaSb layers respetively. Moreover, electrons and holes can be recombined and regenerated by the influence of magnetic field. Whereas, in type I superlattices, such as GaAs/GaAlas, electrons and holes are confined in the same layers (i.e. GaAs) and there is no recombination and regeneration of carriers due to change of magnetic field. In this paper, we have developed a theory of QHE for type II semiconductor superlattices based on the 8x8 **k.p** matrix Hamiltonian, which includes the electron and hole carriers, electron-hole interaction through spin-orbit interaction and the effects of nonparabolicity and anisotropy[2]. By considering this Hamiltonian and taking into account interaction with impurities and Coulomb electron-hole interaction, the conductivity have been calculated by using the linear response theory and Green's function method. The dependance of concentration of carriers have been treated self-consistently. The present theory is used to compare with the experimental results of GaSb/InAs superlattices.

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INTERLAYER COUPLING AND ELECTRON-ELECTRON CORRELATIONS IN Co/Cr/Ag/Co MULTILAYERS

F.G.Aliev, E.Kunnen, J.Barnas, K.Mae, K.Temst, G.Verbanck, V.V.Moshchalkov, and Y.Bruynseraede

Laboratorium voor Vaste-Stoffysica en Magnetisme, K.U.Leuven, Celestijnenlaan 200D, B3001, Leuven, Belgium

We report on electrical transport and magneto-optical studies performed on Co/Cr/Ag/Co multilayer with double nonmagnetic spacer Cr/Ag varying thickness τ(Cr/Ag) between 0 and 47Å and with the same ratio of Cr to Ag. The longitudinal magneto-optical Kerr effect indicates that antiferromagnetic coupling behavior is present for τ(Cr/Ag) of about 5-25Å. The character of the transformation of the magnetoresistance implies transition from anisotropic to spin-valve scattering around τ(Cr/Ar) ~10Å. At low temperatures T<20K the resistivity shows logT increase induced by the electron-electron interactions. The strength of these interactions is found to be correlated with the degree of the exchange coupling.

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Contact Author:

Dr. F.G.Aliev

Laboratorium voor Vaste-Stoffysica en Magnetisme,

Celestijnenlaan 200D,

Katholieke Universiteit Leuven, B3001 Leuven, Belgium

Fax: (3216) 327983

Phone (3216) 327646 , E mail: Aliev.Farkhad@fys.kuleuven.ac.be

THE SURFACE SCATTERING EFFECT ON TRANSPORT PROPERTIES IN THIN Bi-Te WIRES UNDER DEFORMATION

D.Gitsu, E.Condrea, A.Nikolaeva

Institute of Applied Physics, Academiei str.,5, Kishinev, Moldova

The resistance dependences on deformation $R(\xi)$, the longitudinal magnetoresistance $R(H)$ and the temperature dependence $R(T)$ in glass-coated Bi wires of the diameter 0,2-5,0 μm in the range 4,2-300 K were investigated. The change of the energy spectrum of carriers under deformation was observed by the Shubnikov-de Haas oscillations method. Doping with Te impurity leads to considerable changes of $R(\xi)$, $R(T)$, $R(H)$. Decrease of the free path and change of the carrier trajectory due to scattering on impurities leads to the fact that much larger part of electrons gets inside the "reach cone" and reflects from the real surface. Thus, the carrier scattering from the surface becomes considerably diffuse in contrast to the scattering in Bi wires, when electrons are reflected specularly in the subsurface layer of the bulk charge.

The resistance dependence on the temperature for the Bi-0,0025 at.% Te thin wires with the diameter 0,2 μm appeared to be the most interesting. The temperature dependence $R(T)$ shows the semiconducting behaviour, and in the temperature range 4,2-7 K has peculiarities. Such a behaviour is analogous to that of the $R(T)$ dependence found in the experiments [1] on the deformed Bi wires: the resistance increases at the temperature decrease, and at low temperatures there are fluctuations testifying to the beginning of the superconducting junction. Under the deformation influence the $R(T)$ semiconducting behaviour becomes metallic. At the deformation more than 1,5 % on the longitudinal magnetoresistance $R(H)$ the oscillations of the flux quantification type with the period $\Delta\Phi = hc/e$ appear.

As far as the deformation application influences the surface charge distribution, it can lead to the situation typical for semimetals, when the free path becomes much larger than the screening length. Then in the subsurface layer the conditions necessary for appearance of oscillations of the flux-quantification type in normal metals appear.

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Defects in ZnSe thin layers on GaAs(100) substrate grown by VPE and X-ray-assisted VPE

KOVALENKO A. V.
Dnepropetrovsk State University, 72 Gagarina av.,
320625 Dnepropetrovsk, Ukraine

It has been shown that x-ray-assisted VPE (radiation sourse Cukα, λ = 1,542 Å, P= 1-3 mW/cm^2) at low substrate temperatures (170-350° C) and big temperature gradient (200-250° C/cm) give results in extremely pure layers such as ZnSe on GaAs(100). The results of the investigation of the morphology of the surface of the films under an electron microscope and x-ray diffraction analysis show that this methods of growth give us very good samples for different electronic devices. Reflection and pfotoluminescence spectra of the obtained structures (fig.1) have been studied at T = 4.5 K.

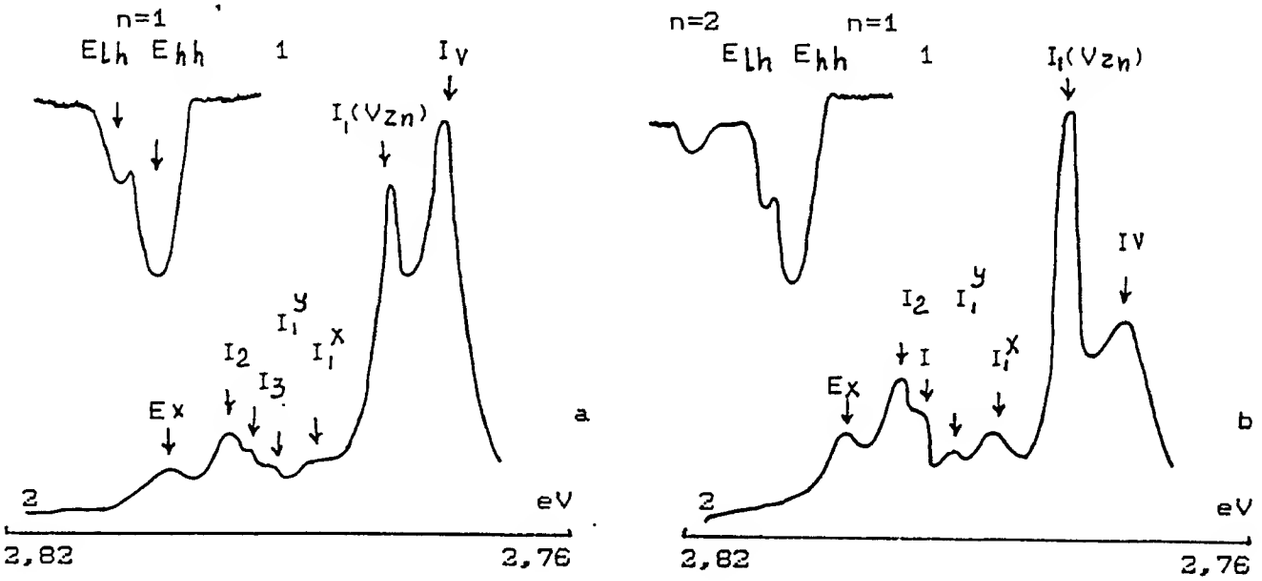

Fig.1. Reflection (1) and pfotoluminescence (2) spectra of ZnSe layers (d = 0,55 mkm) on GaAs (100) substrate grown by VPE (a) and x-ray-assisted VPE (b).

The reflection spectra of x-ray-assisted ZnSe layer having a narrow "pocket" of exciton absorption with quantum dates n=1 and n=2, indicates good single-crystalline quality of the layer and a sharp "layer-substrate" boundary. We assigned the minima at 2,8048 and 2,8034 eV to the fundamental absorption of excitons with different hole masses: E_{lh} and E_{hh} . The pfotoluminescence spectra of this sample shows the increase of intensity some exciton lines: E_x (free exciton), I_2 (Ga), I_3 (Ga), I_1^y (Na), I_1^x (Li), and the dicrease some lines connected with defects in crystal structure of ZnSe: $I_1(V_{Zn})$ and I_V.

It has been investigated mechanism of growth ZnSe layers on GaAs by x-ray-assisted VPE, influence of lattice mismatch on theirs optical properties.

MAGNETOTRANSPORT IN LATERAL SURFACE LATTICES.

E.M.Baskin, M.V.Entin, A.G.Pogosov

Institute of Semiconductor Physics, Russian Academy of Sciences, Siberian Branch,
Prosp. Lavrentyeva, 13, Novosibirsk 630090, RUSSIA.
Fax: (3832)351771, e-mail: Baskin@isph.nsk.su

The 2D periodic and disordered lattices formed by classical specular round scatterers with radii a are studied in a magnetic field. The analysis is based on the partitioning all of the electrons into two groups of colliding and not colliding with antidots. In the case of zero magnetic field and disordered lattice all electron trajectories correspond to colliding motion with mean free path $l = d^2/2a$, where d is the mean distance between antidots ($d \gg a$).

The strong negative magnetoresistance in the moderate magnetic field was found caused by the appearance of electrons not colliding with antidots:

$$\frac{\Delta\rho(H)}{\rho(0)} = -f_p \frac{l^2 + r_c^2 f_p}{l^2 + r_c^2 f_p^2},$$

where the cyclotron radius in magnetic field H, $r_c \gg d$, f_p is the fraction of non-colliding electrons. In disordered lattice the mean value of f_p is $\exp(-2\pi r_c/l)$. The other fundamental property of 2D lattice is the appearance of percolation threshold $4\pi(r_c + a)^2/d^2 = 4.4$ for infinite motion and full localization of electrons with r_c below it.

In a periodical lattice the conductivity diverges due to channelling of low-angle electrons. The divergency can be limited by the mean free path l_i with respect to other scattering mechanisms, $l_i \gg l$:

$$\sigma_{xx} \approx \frac{\pi}{6}\frac{d^2}{2a} \ln \frac{2al_i}{d^2}.$$

or by small magnetic field.

The oscillations of f_p due to commensurability of r_c and d has been studied in regular lattice emphasized on their singularities and statistical properties. The regions of geometrical resonances have been investigated on the basis of dynamic chaos theory and by means of computer simulations. The local (near the resonance) and global pictures of the phase space were obtained. The phase space regions corresponding to regular colliding (runaway) motion were found. The fine structure of dynamic chaos of these trajectories caused by the high-order resonances leads to fractal structure of the magnetic field dependencies of kinetic coefficients. Rough structure of the conductivity is determined by low-order resonances.

Peculiarities of PbS layer growth by laser ablation on terrace-step substrate.

J.Vaitkus, L.Barauskaitė, V.Kazlauskienė, J.Miškinis, J.Sinius

Semiconductor Physics Department & Institute of Materials Science and Applied Research, Vilnius University, Sauletekio al. 9 - III, 2054 Vilnius, Lithuania

The possibility to growth a self-organized laterally modulated superlattice on slightly misoriented substrate was demonstrated mostly for III-V compounds and mesoscopic structure (quantum wire net or quantum dots) growth on slightly misoriented substrate become popular. In this work the analyze of growth of IV-VI compounds on terrace step substrate has been initiated to investigate a change of surface chemical activity and to investigate a possibility to influence on photoconductivity parameters by a geometry of layer structure of these photoconductors. The deposition on the substrates with a significant substrate and material lattice mismatch was chosen to induce the quantum dots growth.

The PbS layer growth by laser ablation on Si(100), NaCl (100), on slightly misoriented NaCl (100) and Si (111) substrates has been investigated by means of XPS. The influence of the surface terrace step structure on components chemical shift was found. The broadening and shift of the lead core levels photoelectron spectra peaks have been observed. The substrate atom core level spectra investigation demonstrated a monolayer growth, but with increase of number of monolayers, the additional Pb 4f and 5d spectra components, shifted by approximately 0.6 eV (or more, if the spectra was devided into the components,) were observed in the layers grown on terrace-step surface. These additional peaks were related to a nanometric Pb clusters growth. The additional deposition of Pb on a "flat" PbS layer gave the same Pb lines. After a long deposition the microscopic Pb clusters were grown and they were located at a substrate terrace edges. A rather high diffusion rate was found at rather low temperature substrate. A possibility to form the PbS mesoscopic structures was analyzed, too, paying attention of the layer components spectra broadening.

The supplementary investigation of PbS thin layer structure properties were analyzed by PbS-Si structure photoconductivity measurement. The spectral dependence of photoconductivity was analyzed and a possibility to reveal the PbS nanocrystal influence was proposed. That data supported a model of a substrate terrace-step induced reconstruction of PbS layer structure.

ADSORPTION ON A SURFACE WITH ARTIFICIAL DEFECTS: METHOD OF NANOSTRUCTURES FABRICATION.

Yu.E. Lozovik, A.M. Popov

Institute of Spectroscopy, Russian Academy of Science, 142092, Troitsk, Moscow region, Russia; e-mail:lozovik@isan.msk.su

The development of scanning tunneling microscopy (STM) and atomic force microscopy (AFM) give rise to the elaboration of a lot of methods to modify a surface by the presence of artificial defects. In connection with this nanotechnology advance the theory of adsorption of particles (atoms and molecules) on a surface with defects is proposed.

The thermodynamics and kinetics of the adsorption is considered taking into account two possible adsorption positions: on defects (D) and on the surface free of defects (F). The equations for concentrations of particles adsorbed on adsorption positions D and F are derived with the help of both approaches. The adsorption of argon atoms and acetylene and benzene molecules on the graphite surface with pits made by removal of several atoms or several tens of atoms is simulated. Adsorption energies, frequencies of oscillations and concentrations of particles adsorbed in pits were calculated. It is shown that the adsorption energy is determined by shape and size of the pit. Therefore it is shown that defects may *selectively* affect on the adsorption of particles. Optimal pits corresponding to the maximum adsorption energy for cases considered are found. It is shown that in the considered cases it is possible to increase the concentration of particles adsorbed on the surface with optimal pits by orders of magnitude in comparison with that for ideal surface.

The indroduced theory allows us to propose new nanotechnological applications of adsorption on the surface with artificial defects:

1) Pattern transfer. The artificial defects increasing the adsorption energy of particles may be nucleation centers for formation of islands from the particles depositing on the surface. Islands around defects may also form during the desorption of a film. This artificial defects may be used for the pattern transfer with the help of *self-organization* of deposited particles. If the defects are positioned with the help of STM or AFM according to certain scheme the formed islands would merge into certain pattern. Moreover, we propose to create different defects *selectively* increasing the adsorption energy of different particles. In this case the self-organization of mixture of different particles deposited on the modified surface give rise to pattern made from different materials.

2) Supersensitive sensors. We propose also to use the selective adsorption on the surface modified by presence of artificial defects for elaboration of the sensors supersensitive to certain molecules.

3) Separation of isomers. A surface can be modified to have pits capable of accommodating only one of several isomeric molecular species. We suggest using such a modified surface to detect or separate molecules differing in shape only.

Superconductivity in mesoscopic Al multiloop structures*

V. Bruyndoncx, C. Strunk, V. V. Moshchalkov, C. Van Haesendonck, and Y. Bruynseraede

Laboratorium v. Vaste-Stoffysica en Magnetisme, Katholieke Universiteit Leuven,
B-3001 Leuven, Belgium

Small superconducting loops exhibit a well-known $h/2e$ periodic modulation of the transition temperature T_c with the enclosed magnetic flux Φ, which is due to the fluxoid quantization. We have found substructures of this modulation in the magnetoresistance $R(\Phi)$ and the magnetic phase boundaries $T_c(\Phi)$ of microladders containing several square loops of 1.3 μm size. The substructures are due to transitions between superconducting states differing in the order parameter profile and the flow pattern of the supercurrents. The experimental data are in excellent agreement with the theoretical phase boundaries obtained within the de Gennes-Alexander[1] approach for superconducting micronetworks.

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Contact author:
Dr. Christoph Strunk
Address:
Laboratorium voor Vaste-Stoffysica en Magnetisme
Celestijnenlaan 200D
B-3001 Leuven
Belgium

Fax: 32-16-327983
Phone: +32-16-327120
E-mail: Christoph.Strunk@fys.kuleuven.ac.be

FABRICATION AND TRANSPORT STUDIES OF ULTRA- NARROW QUANTUM WIRES (QW) AND QW SUPPERLATTICES

V.Ya.Prinz, V.A.Seleznev, A.B.Vorob'ev

Institute of Semiconductor Physics, Russian Academy of Science, 630090, Novosibirsk, Russia

Recently, a new technique for fabricating nano- and atomic scale device elements and quantum system has been proposed which cannot be obtained by any other known technology [1,2].

The technique is based on experimentally established possibility to create ultra-narrow (1 nm) and perfectly straight atomically sharp-edged cracks of a desired length and direction in a given layer of a A^3B^5 heterostructure.

This work presents further development of the maskless fabrication techniques. It is aimed at fabrication of ultra-narrow (3 nm) quantum wires (QW) and QW supperlattices. The work employs such unique properties of the obtained slits in epitaxial layers as i) ultra-narrow width, ii) atomically-sharp edges, iii) practically constant width along the slits, iiii) perfectly straight boundaries free of roughness (atomically flat faces). Since the gap between crack edges in a GaAs/InGaAs structure is very small (typically less than 3 nm) it becomes possible to realize either inversion or accumulation at one of the edges by applying a voltage between edges. In the GaAs/InGaAs multistructure used in our experiments, the conducting accumulation regions were located in narrow-band InGaAs layers, which set limit to the QW thicknesses.

We also describe experiments in which annealing the structures with introduced cracks in the presence of liquid metal resulted in subsequent filling of slits with molten material through capillary action.

Measurements of conductivity and magneto- conductivity in QW have been performed at different temperatures ranged from 4 to 300 K.

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TRANSPORT PROPERTIES OF AlAs/GaAs MULTILAYER STRUCTURES GROWN ON (311)A GaAs SUBSTRATES.

I.A.Panaev, V.Ya.Prinz, A.B.Vorob'ev, V.V.Preobrazhensky, B.R.Semyagin

Institute of Semiconductor Physics, Russian Academy of Science, 630090, Novosibirsk, Russia

The direct synthesis of quantum wires during the growth of GaAs/AlAs superlattices on the GaAs (311)A surface has attracted much interest [1,2]. Grown on (311)A substrate surface lateral superlattices of GaAs quantum wires with extremely small diameter, 20A, have a strongly anisotropic p-type conductivity up to room temperature [2]. To obtain high-quality structures with ultra-small quantum wires, we carried out a variety of growth optimisation experiments. It has been shown that the ratio of the conductivity at 77 K along the wires to that in the perpendicular direction varied in the range between 8 to 3 being dependent on the time of growth interruption of heterostructures, their doping level and other growth conditions. Conductivity in direction perpendicular to the wires was very similar in all structures. The dynamics of electron diffraction intensity has given clear evidence of the facet formation under the growth condition used. In addition to clearly pronounced oscillations, corresponding to deposition of six (311) monolayers, at a specific choice of the diffraction conditions we could observe a monolayer oscillation, which could be due to the layer-by-layer growth mechanism on the (311)A surface. Systematic studies of transport properties of Be-modulation-doped (p-type) AlAs/GaAs multilayer structures with AlAs layer thickness of 27A and GaAs one ranging from 4 to 21A in different samples have been carried out. The transformation of transport properties from the 2D-like to those of quantum-wire-well superlattices (QWW SL) (11-21A) and wire-like clusters (4-8A) has been investigated. It has been shown that temperature behaviour of the hole gas concentration has an activated character. The activation energy has been found to increase with the decreasing GaAs thickness. The Si-modulation-doped (p- and n-type) QWW SL were also grown. In contrast to p-type structures there was not observed any anisotropy in conductivity of n-type structures doped with Si and containing GaAs(21A)/AlAs(27A) QWW SL. The experimental results and prospects for the application of this structures in the practical devices have been discussed.

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ELECTRONIC EXCITATIONS IN COUPLED QUANTUM WELLS

V.S.Vinogradov
P.N.Lebedev Physics Institute, Leninsky Prospect 53,
Moscow 117924, Russia

The effect of the tunnel coupling and subband filling on the dispersion laws of the electronic excitations (EE) in multi-quantum-well structures is theoretically investigated. The following questions are considered:

1) The effect of the subband filling on the dispersion laws of the intrasubband (2d-plasmon) and intersubband EE.

2) The softening and possible instability of the intersubband mode in the symmetric two-well structure relative to appearance of the state modulated along the quantum well surface.

3) The influence of tunnel coupling in the multi-quantum-well structure on the plasmon mode at large wave vectors when the tunnel coupling is greater than the Coulomb's one.

4) The interaction of the plasmon and intersubband modes in the symmetric two-well structure under the electric field.

The EE energies of multi-quantum-well structures usually occur in infrared spectral region. Application of the infrared and Raman spectroscopy in combination with theoretical results allows to determine the multi-quantum-well structure parameters.

LO-PHONON EFFECTS ON THE EXCITONIC ABSORPTION OF ZnCdSe/ZnSe QUANTUM WELLS

A.Camacho, F.J.Rodríguez and L.Quiroga

Departamento de Física, Universidad de los Andes, A.A.4976, Bogotá, Colombia.

We study the excitonic absorption spectrum of undoped wide-gap II-VI systems. The Bethe-Salpeter equation is solved in a two band model for finite quantum wells (QW's). The electron-hole Coulomb correlation and exciton-LO-phonon interaction are treated on equal footing. Our calculation scheme allows us to follow the evolution of the optical spectrum of $Zn_{1-x}Cd_xSe/ZnSe$ QW's from weak to strong exciton binding energy as compared with the LO-phonon energy. We found that the exciton-phonon interaction decreases the binding energy and the oscillator strength. A systematic study of the full width at half maximum (FWHM) of the exciton absorption peak as a function of Cd well composition, and width, is performed. We found that for thin wells the effects of the exciton-phonon coupling is weak while for thick wells this coupling is enhanced by a reduction of the exciton binding energy below the phonon energy. Satisfactory agreement with recently experimental situation is obtained.

Universal conductance fluctuations and the impurity potential configuration in GaAs δ-layers.

M.V.Budantsev, Z.D.Kvon, E.B.Ol'shanetskii, A.G.Pogosov

Institute of Semiconductor Physics, Novosibirsk, Russia

In this work we report a method of determination of the impurity potential configuration in heavily doped semiconductors from the universal conductance fluctuations (UCF) measurements. The method is founded on the Fourier analysis of magnetoresistance data in heavily doped semiconductor structures of small size. We present the results obtained by this method for GaAs δ-doped layers.

According to the theory of UCF if the fluctuational potential is formed by randomly situated scatterers, the Fourier power spectrum (FPS) of the corresponding UCF has a $1/B$ dependence. In the present work we show that it is not always so in structures fabricated on the basis of GaAs δ-layers. The impurity potential configuration in a δ-layer may turn out to be more complex as compared to a random one and it is shown here how the analysis of FPSs can provide some information about its actual structure.

We employed small-sized samples prepared from δ-doped GaAs layers grown by the molecular-beam epitaxy. The parameters of the initial layers at 4.2K were as follows: the mobility was μ=2000–4500cm^2/Vs and the electron density was N_S=(3.5–6)·10^{11}cm^{-2}. The structures were fabricated by means of electron beam lithography and consequent reactive ion etching and had the length L=1μm and the width W=0.1–0.2μm. All conductance measurements were performed at temperatures 1.3–4.2K and in magnetic fields up to 8.1T.

The FPSs derived from the magnetoresistance data were found to differ considerably. In most cases they do not have the conventional $1/B$ dependence. For some of the samples the FPSs has a distinct maximum. The position of this maximum is individual and depends on a sample. We suppose that this behavior may be indicative of the existence of dielectric clusters in GaAs δ-layers. If so, the characteristic size of such a cluster may be determined from the position of the FPS maximum. In studied samples this characteristic size is about 50–100nm. It is the first evidence of the existence of dielectric clusters in GaAs δ-layers.

ThP Poster session

Ground-state exciton condensate in a coupled electron-hole system

Y. Naveh and B. Laikhtman

Racah Institute of Physics, The Hebrew University, Jerusalem

The coupling between electron and hole (e-h) states in InAs-GaSb double quantum well structure leads to a very strong electric-field-tunability of its 2D band structure[1]. In particular, the semiconducting gap can be tuned to a value smaller than the exciton binding energy, thus achieving an exciton-condensate phase as the ground state of the system. We present detailed, realistic calculations of this state at low temperatures. Our model Hamiltonian includes both the direct and exchange interaction terms, and the strong e-h hybridization is taken into account. The results indicate the appearance of a BCS-like gap of the order of $3 - 5\,\mathrm{meV}$, which vanishes in a sharp phase transition with electric field. In addition to exhibiting a stable ground state excitonic phase, the studied system is unique in two more senses. It allows the continuous change of the condensate density, and thus the direct probe of the Bose-Einstein to BCS crossover. It may also serve as an ideal platform for the study of the debated notion of double-layer superconductivity, for the carrier motion is truly 2D when e-h coupling exists, but becomes of double-layer nature when the coupling is suppressed (*e.g.*, by a thin AlSb barrier layer).

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SPIN RELAXATION OF CARRIERS PHOTO-EXCITED IN DOPED SEMICONDUCTOR HETEROSTRUCTURES

M. Z. Maialle and M. H. Degani
Departamento de Física e Física Aplicada. Universidade São Francisco
Itatiba - SP, 13251-900, Brazil

Photo-excitation of carriers in III-V semiconductor heterostructures by a short pulse of polarized light, followed by measuring the polarization of the luminescence with refined time resolution, has been extensively used to investigated the relaxation dynamics of the angular momentum (spin) of the injected carriers.

In this work, we introduce an original theoretical model which incorporates simultaneously two important spinflip mechanisms in order to explain the spin relaxation of holes (electrons) excited in *n*-doped (*p*-doped) samples. We start with a self-consistent calculation of the energy levels of the doped heterostructure following the split-off--operator method applied to semiconductors[1]. Thus, the choice of the heterostructure profile and impurity distribution is open to describe a wide range of two-dimensional systems. The spin mixing in the valence band is calculated by spanning the valence states in terms of the unmixed-spin states at $k_{//} = 0$, and by diagonalizing the effective hamiltonian [2]. This provides the basis to describe the spinflip mechanism which relaxes the hole spin by momentum scattering. The second mechanism in our theory is the e-h exchange interaction, which flips the carriers' spins during e-h scattering, as it was first worked out in the theory of Bir, Aronov and Pikus[3] (BAP process) in the bulk, and more recently extended to quantum wells[4]. Here, we show how the combined effects of the valence spin mixing and the BAP scattering cause spin relaxation in realistically modeled semiconductor heterostructures. We discuss how this spin relaxation process is affected by different heterostructure profiles, carrier densities, excitation energies, and other variables of the problem.

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The inter-island energy transfer and the in-plane exciton migration in AlGaAs/GaAs quantum wells detected by exciton dynamics

M. Godlewski [1] P.O. Holz [2], J.P. Bergman [2], B. Monemar [2],K. Reginski [3], M. Bugajski [3], E.M. Goldys [4], T.L. Tansley [4]

[1] Inst. of Physics, Polish Acad. of Sci., 02-668 Warsaw, Al. Lotnikow 32/46, Poland,
[2] Dept. of Physics and Meas. Technol., Linkoping University, S-581 Linkoping,Sweden,
[3] Institute of Electron Technology, 02-668 Warsaw, Al. Lotnikow 32/46, Poland,
[4] Semicond. Sci. and Technol. Labs, Macquarie Univ., North Ryde NSW 2109, Australia.

We present results of optical, steady state and time resolved studies of photoluminescence (PL) and PL excitation (PLE) in high quality quantum well (QW) grown without growth interruptions at the interfaces in the $Al_{0.3}Ga_{0.7}As/GaAs$ system. By selectively exciting into the heavy hole (HH) exciton resonance we were able to resolve several components of the PL emission and relate them to the presence of large (compared to the exciton radius), relatively flat regions of the QW differing in width by one monolayer. We show that different excitation energies lead to entirely different multi-component emission spectra, clearly resolved in the case of excitation resonant with the HH excitons. Their identification is based on the analysis of the PLE spectra and accurate calculations. Similar unresolved PL components are responsible for a single-line PL for a non-resonant excitation. The results of the time resolved measurements of the multi-component HH exciton emission in the case of resonant and non-resonant excitation explicitly show that excitons drift towards lower energies states in the QW plane. This drift is attributed to migration of excitons towards lower-lying energy states induced by local potential fluctuations and/or progressive localisation. Potential fluctuations present in QW structures result from random composition and QW width variations and/or imperfect interfaces. We analyse the time - dependent PL emission results by separating the effects of drift from the effects of the radiative decay. We present direct evidence for the free exciton migration from the 24 to 25 ML regions of the QW and interpret these results within a linear rate model, deriving the transition rate of $290ps^{-1}$. Finally we establish the relationship between the obtained linewidths, the Stokes shift and the radiative decay time.

GaAs quantum well islands formed by sub-monolayer AlAs masking and thermal desorption

Timothy A. Strand, R. L. Naone, L. A. Coldren, P. M. Petroff, and E. L. Hu

National Science Foundation Center for Quantized Electronic Structures (QUEST)

Electrical and Computer Engineering Department and Materials Department

University of California – Santa Barbara

Santa Barbara, CA 93106

Abstract:

The high surface-to-volume ratios in small optoelectronic and electronic devices result in high levels of current lost to surface recombination. We present a technique aimed at eliminating this loss by reducing the lateral diffusion of carriers in a quantum well. We deposit, by molecular beam epitaxy, a fractional monolayer of AlAs onto a GaAs quantum well. The AlAs forms discrete islands which are stable under arsenic flux at temperatures over 700°C. At these elevated temperatures the GaAs which is not covered by the AlAs islands begins to desorb, resulting in a patterning of the quantum well into discrete islands. This provides a barrier to the lateral diffusion of carriers, which would otherwise supply the surface recombination process. We present data showing the size, shape, and distribution of these quantum well islands, as well as measurements of luminescence and carrier diffusion. We demonstrate lateral diffusion lengths in quantum well island layers as small as 0.27 μm, and luminescence efficiency comparable to that of a non-patterned quantum well. We also discuss the applicability of this technique to forming quantum boxes.

Phase Transition in a Two-Dimensional Dipole-Oriented Exciton System

T. Fukuzawa[A], S.Y. Kim[B], T.K. Gustafson[B], E.E. Haller[C], and E. Yamada[D]

A: PRESTO, JRDC, c/o IBM Research, Tokyo Research Laboratory,
1623 Shimotsuruma, Yamato-shi, Kanagawa-Ken 242, Japan
B: Electrical Engineering and Computer Science, University of California, Berkeley, CA 94720, USA
C: Material Science and Mineral Engineering, University of California, Berkeley, CA 94720, USA
D: Information Science, Meisei University, Nagabuchi, Ome-shi, Tokyo 198, Japan

In contrast to the ultra-cooled alkaline atoms[1], excitons in semiconductors have the possibility of exhibiting Bose-Einstein condensation at a relaxed low-temperature requirement. A dipole-oriented 2-dimensional (2D) exciton system in GaAs/AlGaAs coupled quantum wells (CQWs) with electrical bias is one such candidate[2]. This system is unique in that the boson density can be freely varied by optical excitation and the energy distribution can be monitored by measuring the recombination radiation. At the last conference[3], we reported initial indications of a possible phase transition at temperatures below 5K.

In continuing experiments with several samples, we have consistently observed the same anomaly with similar quantum well structures. Figure 1 shows the excitation intensity I_{ex} dependence of the average energy per photon E_{av}, which is obtained by observing the photoluminescence spectra at different temperatures. At high temperatures, dipole-oriented excitons have sufficient energy to hop around in a 2D plane, although there is a sample-dependent potential roughness[4]. Decreasing temperature restricts the hopping region to the vicinity of the exciton birth place and decreases the chance of reaching lower energy sites. This increases the E_{av} in the low temperature range. The anomaly occurs below a critical temperature T_c and at a critical density n_c, for which the de Broglie wavelength λ exceeds the average inter-particle distance. The abrupt decreases in E_{av} vs I_{ex} curves at 5K, 3.79K and 1.97K provides evidence of the possibility of a 2D Bose-glass-to-superfluid transition.

Our system consists of 2D bosons with repulsive interaction in a potential with roughness. Quantum statistical properties of 2D bosons can be calculated by path-integral Monte-Carlo simulation in which 2D bosons are mapped onto strings of directed polymers in 3D[5]. The interplay between quantum correlation, coulomb repulsion and surface disorder can be analized and future possibilities should be predicted by this method.

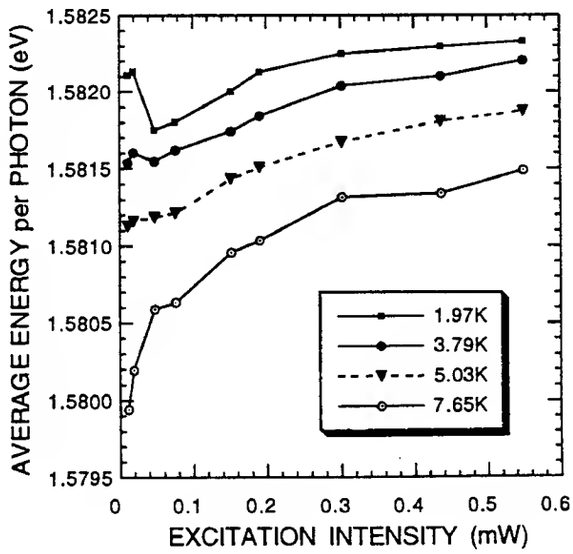

Fig. 1: Average photon energy vs. excitation intensity, calculated from the PL spectra for various temperatures and excitation densities.

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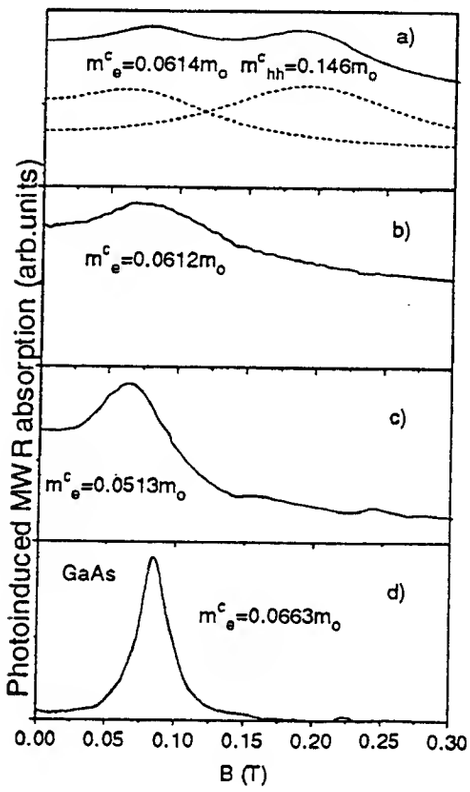
PROPERTIES OF PHOTOEXCITED ELECTRONS AND HOLES IN UNDOPED GaAs/AlGaAs QW's STUDIED BY CLASSICAL CYCLOTRON RESONANCE

M. Kozhevnikov, B.M. Ashkinadze, E. Cohen, Arza Ron and L.N. Pfeiffer[1)]
Solid State Institute, Technion, Haifa 32000, Israel, Fax 972-4-235107
[1)] AT&T Bell Laboratories, Murray Hill, NJ 07974, USA

Despite the great progress in understanding QW band structures and exciton phenomena in undoped QW's, little is known about photoexcited unbound electrons and holes in QW's, namely, about their photogeneration, recombination and momentum (energy) relaxation processes. Microwave radiation (MWR) absorption by the photogenerated carriers and , in particular, classical cyclotron resonance (CR) provides a sensitive and contactless probe of their properties. We studied MWR (35.6 GHz) absorption in undoped GaAs/AlGaAs QW's having different well widths and in ultra pure bulk GaAs. We report on the first direct observation of a classical electron and hole CR in undoped QW's (Fig.a). In ultra pure GaAs the extremely high electron mobility ($2x10^6 cm^2/Vs$ at T=1.6K) is deduced from the CR, and the mechanisms of low-temperature electron momentum relaxation are studied. In QW's, the effects of photoexcitation energy and intensity (I_L), photomodulation frequency as well as of electron and lattice temperatures on the CR magnetic fields and linewidths are studied. It is found that the electron cyclotron mass (m_e^c) increases with increasing I_L, MWR power (P_{mw}), photomodulation frequency (up to 1 MHz) and with the lattice temperature. This will be discussed in terms of a decreased electron localization in the spatially fluctuating QW potential [1,2].



The figure shows CR traces for a 7/20 nm GaAs/AlAs MQW (a,b,c) and for bulk GaAs (d) for various I_L (mW/cm^2) and P_{mw} (mW) at T=6K: (a) 300 and 50, (b) 3 and 50, (c)-(d) 3 and 0.05. The m^c are obtained by fitting the CR traces using the Drude formula. An example of this fitting is shown in (a) by dashed lines.

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Experimental and theoretical study of the light-hole band-edge configuration in $In_xGa_{1-x}As/GaAs$ multiple quantum wells

T Worren[1], O Hunderi[1], E Selvig[2] and B O Fimland[2]
[1]*Department of Physics,* [2]*Department of Physical Electronics,*
Norwegian University of Science and Technology, N-7034 Trondheim, Norway

We will present an experimental and theoretical study of $In_xGa_{1-x}As/GaAs$ multiple quantum wells (MQWs) specially designed to determine whether the MQW is of type I or type II for the light-hole/electron system. Earlier studies by other groups have given contradictory results[1] on this topic.

The samples were grown by MBE, and the sample parameters were checked by high resolution X-ray diffraction. The samples were designed as follows: two and two samples have the same indium content and InGaAs-layer widths, but different GaAs-layer widths. If the MQW is of type II, the light-holes will be (more or less) confined to the GaAs-layers, while the electrons are confined to the InGaAs-layers. The confinement energy for the light-holes is then more dependent on the width of the GaAs-layers, than if the MQW is of type I. Also the electron and heavy-hole energy levels are influenced (but much less) by the change in barrier width, and therefore we have studied the change in the splitting of the e1hh1 and the e1lh1 transition energies. This splitting will increase in the order of meV (tens of meV) when the barrier width increases, for type I (type II) MQWs.

We have calculated the potential profiles using the absolute energy positions of the band-edges taken from the model-solid theory,[2] including strain. The energy levels were calculated using the effective mass approximation in a transfer matrix formalism. We took into account the discontinuity of the lattice constant along the growth direction, and the fact that the cap-layer is of finite width and the vacuum barrier of finite height.[3] Furthermore. we also calculated the overlap-integral of the electron and hole wavefunctions.

We have performed PLE spectroscopy (sample temperature 11K) on five pairs of InGaAs/GaAs MQWs (4 periods) with In concentration in the range 5.5% to 23.5%. To unambiguously identify the e1lh1 transition we performed polarized PLE (PPLE), with linearly polarized light. Comparison of the PLE spectra showed that for the samples with an In content smaller than 16.6%, the e1hh1-e1lh1 splitting was from 3 to 15 meV smaller for the wide barrier samples than the narrow barrier samples. This, together with comparison of the linewidths. suggests that a MQW with these In concentrations is of type II for the light-hole/electron system, and that the transition from type II to type I is for an In content between 16.6% and 20%. This is in agreement with results from our calculations.

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UP-CONVERSION LUMINESCENCE VIA A BELOW-GAP STATE IN GaAs/AlGaAs QUANTUM WELLS

*N. KAMATA, K. HOSHINO, T. UCHIDA, K. YAMADA, M. NISHIOKA * and Y. ARAKAWA **
Department of Functional Materials Science, Saitama University, 255 Shimo-Ohkubo, Urawa
Saitama 338, Japan//fax:+81-48-855-0940, e-mail:kamata@d-butsu.ees.saitama-u.ac.jp
* Institute of Industrial Science, The University of Tokyo, Roppongi, Minato-ku, Tokyo 106, Japan

We have observed a band-to-band photoluminescence(PL) of the well layers in GaAs/AlGaAs quantum well structures only by the below-gap excitation(BGE) of a Nd:YAG laser (1.17eV). A detailed study by changing the density of both the BGE and the above-gap excitation(AGE) of a He-Ne laser(1.96eV) revealed the mechanism of a cascade excitation via a below-gap state for the first time. The origin was inside the epitaxially-grown well layers and was different from those in GaAs substrates[1].

Samples were GaAs/$Al_{0.2}Ga_{0.8}As$ quantum well structures with 20 wells(7nm) and 21 barriers(7nm) grown by MOCVD. Sample M1 was undoped, while samples M2, M3 and M4 were Se-doped with the concentration of $7.5x10^{16}$, $5.0x10^{17}$ and $2.0x10^{18}$ [cm^{-3}], respectively. The up-conversion PL was observed in samples M1 and M2 at 77K. Their normalized spectra coincided fairly well with those of the PL under the AGE: The intensity of the up-conversion PL was proportional to the BGE density(Fig. 1). Samples M2, M3 and M4 showed impurity-band PL in addition to the band-to-band PL.

In order to clarify the mechanism, a below-gap excitation spectroscopy[2] was carried out:The spotsize of both the AGE and the BGE was adjusted on the sample surface with the aid of IR-scope and the PL spectrum as functions of both the AGE and the BGE density was recorded based on a photon-counting technique. With increasing the BGE density under fixed AGE, the PL intensity of M1 and M2 increased while that of M3 and M4 decreased, indicating the different nature of below-gap states among these samples.

Our rate-equation analysis attributed above results to two origins of below-gap states. One is a native defect in undoped crystals, through which the PL intensity increases and the up-conversion takes place with increasing the BGE. The other is a set of two below-gap levels[3], possibly a dopant(Se)-complex, which becomes dominant when doping concentration exceeds 10^{18} [cm^{-3}]. It decreases the PL intensity since the inter-level excitation due to the BGE increases the rate of non-radiative recombination. Both the AGE and the BGE density dependence of the band-to-band, up-conversion and impurity-band PL agreed well with the analysis.

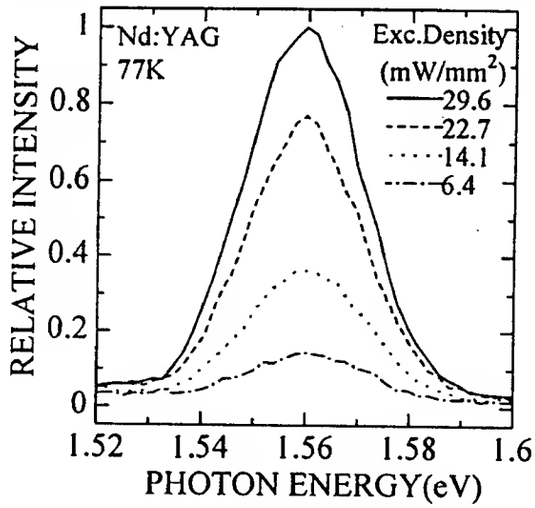

Fig. 1 Up-conversion PL of M1 as a function of the BGE density.

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SPIN DEPENDENT PROCESSES IN EXCITON-ELECTRON SCATTERING IN QUANTUM WELL STRUCTURES WITH A 2DEG

V.Kochereshko, A.Platonov

A.F Ioffe Physico-Technical Institute RAS, 194021, St.Petersburg, Russia

Franck Bassani, R.T.Cox

CEA-Grenoble, 17 Rue des Martyrs, 38054 Grenoble, France

The contribution of spin flip-flop processes to exciton - electron scattering was found in quantum well (QW) structures with low-density two-dimensional electron gases. Pronounced polariton effects were observed in the structures' optical transmission.

The structures studied were MBE grown 100 Å CdTe / 450 Å $Cd_{.85}Zn_{.15}Te$ multiple quantum wells modulation- doped at the 450 Å barrier centers to give 10^{10} to 10^{11} electrons cm^{-2} in each CdTe well.

Photoluminescence (PL) spectra consisted of two lines corresponding to recombination of the e_1-hh_1 free exciton (FE) and of the negatively charged exciton (X^-). The X^- intensity depends on the electron concentration in the QW. In a magnetic field at low temperature, complete (100%) circular polarization of X^- was observed in PLE, transmission and reflectivity, due to the electron spin polarisation. At the same time a partial circular polarization was observed in PLE and in transmission for the free exciton. The sign of the polarization of the FE line was opposite to that observed for the X^- line. We extracted the excitonic parameters by analyzing the reflectivity and found a difference of exciton damping for $^+$ and $^-$ circular polarization. This difference in damping was found to be dependent on the free electron concentration in the QW. The observed polarization dependence of the exciton damping is explained by the contribution of spin flip-flop processes of exciton - electron scattering in the low density 2DEG in a magnetic field. In this cooperative process, the photogenerated exciton loses its energy by scattering to the orthoexciton state (S=2) and the electron is simultaneusly excited to its upper Zeeman sublevel. We show that the cross section for such a process is not small at these intermediate electron concentrations. A one order of magnitude increase of the spin relaxation rate due to this process was measured. From analysis of the transmission spectra, we found a spin dependent increase of the dissipative contribution to exciton damping compared to radiative damping. The temperature dependence of the exciton damping shows pronounced polariton effects : the radiative excitonic processes may be larger than the nonradiative processes.

Temperature dependent photoluminescence of Te-doped GaSb/AlSb superlattices

Guoping Ru, Aizhen Li and Yanlan Zheng

State Key Laboratory of Functional Materials for Informatics

Shanghai Institute of Metallurgy, Chinese Academy of Sciences

Shanghai 200050, China

Wenzhong Shen

National Laboratory for Infrared Physics

Shanghai Institute of Technical Physics, Chinese Academy of Sciences

Shanghai 200083, China

Temperature dependent photoluminescence (PL) of Te-doped GaSb/AlSb superlattices grown by molecular beam epitaxy is presented in this paper. PL measurements were performed in a Nicolet 800 Fourier transform infrared spectrometer over temperature range of 4 K to room temperature. Fig. 1 shows the PL spectra of four n-doped GaSb/AlSb superlattices with different well width at 77 K. Solid line and solid dots in the inset indicate theoretical and experimental value of E_1-HH_1 recombination energy, respectively. Detailed temperature dependent study was performed on the sample with well width of 90 Å. The integrated PL intensity is found to be nearly proportional to excitation power at 4 K, i.e., $I_{PL} \propto I_{ex}^{1.09}$, as shown in Fig.2. Fig. 3 shows the linewidth Γ of PL peak as a function of temperature. From linewidth analysis, the inhomogeneous linewidth is determined to be 88 meV and the exciton-phonon coupling strength is determined to be 564 meV. Fig. 4 shows the integrated PL intensity as a function of inverse of absolute temperature. From the best fitting analysis, the quench of photoluminescence is thought to be the activation of nonequilibrium electrons from Γ_1 to L_1 subband.

Effect of tensile strain on optical properties of AlGaP-based neighboring confinement structure

T. Ohta, N. Usami, F. Issiki, and Y. Shiraki
Research Center for Advanced Science and Technology (RCAST), The University of Tokyo,
4-6-1 Komaba, Meguro-ku, Tokyo 153, Japan

We report on the effect of tensile strain on optical properties of AlGaP-based neighboring confinement structure (NCS), which has been proposed to improve the photoluminescence efficiency of indirect semiconductors[1]. NCS consists of a pair of AlP/GaP type-II heterostructure sandwiched between AlGaP barrier layers. Remarkably enhanced photoluminescence intensity has been observed from NCS compared with AlP/GaP superlattices. In this study, introduction of tensile strain to NCS was examined aiming at improving luminescence efficiency owing to both Γ-X mixing effect and enhancement of the penetration of the wave function into barrier layers.

The tensile strain was induced by growing AlGaP-based NCS (10Å-AlP/10Å-GaP on $Al_{0.5}Ga_{0.5}P$) pseudomorphically on relaxed-$In_xGa_{1-x}P$ (x=0.053 to 0.10) buffer layer on GaP (001) substrates by using gas source MBE. The photoluminescence intensity of tensilely strained NCS was found to be remarkably increased especially in samples with x=0.093. In addition, dramatic increase of the activation energy for thermal quenching of luminescence was achieved by introduction of tensile strain in spite of reduction in the confinement energies of the well. In unstrained systems, the activation energy was seen to be much smaller than the total confinement energy of the electron and hole. This is probably attributed to the extrinsic factor, that is, the dominant nonradiative recombination process at heterointerfaces between the well and AlGaP barrier layer. On the other hand, in strained systems, the thermal behavior was shown to be intrinsic, that is, the thermally activated escape of electron-hole pairs from the well into AlGaP barrier layers dominates the process. This improvement of the activation energy would be explained in terms of the isolation of the exciton from the nonradiative centers possibly due to the local strain variation originating from the alloy randomness of InGaP buffer layer. So, introduction of tensile strain to NCS is considered to induce not only Γ-X mixing effect and the penetration of the wave function but also formation of the deeper bound exciton states.

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Photoluinescence and Photoluminescence Excitation of AlGaAs/GaAs Single Quantum Wells with Growth Interrupted Heterointerfaces Grown by Molecular Beam Epitaxy

Hisao Nakashima, Toshikazu Takeuchi, Koichi Inoue,

Toshiaki Fukunaga*, Dieter Bimberg**, and Jürgen Christen***.

The Institute of Scientific and Industrial Research, Osaka University,
8-1 Mihogaoka, Ibaraki, Osaka 567, Japan
*Fuji Photo Film Co. Ltd. Miyanodai Technology Development Center
798 Miyanodai, Kaisei-Machi, Ashigarakami-gun, Kanagawa 258, Japan
**Institut für Festkörperphysik, Technische Universität Berlin,
Hardenbergstraß 36, 1 Berlin 12, Germany
***Institut für Experimentells Physik, Otto-von-Güericke
Universität Magdeburg, Universitätplatz 2, D-39016 Magdeburg, Germany

AlGaAs/GaAs single quantum wells (SQW) with growth interrupted heterointerfaces (GHI) show three or four photoluminescence (PL) peaks originating from different monolayer (ML) terraces[1]. These ML peaks exhibit a doublet splitting[2]. In this paper, we report on the PL excitation (PLE) of SQW's with GHI and the well width dependence of the doublet splitting.

Samples were grown at 600℃ at rate of 0.5 μm/h. The growth was interrupted for 2min. at both QW interfaces. The magnitude of doublet splitting of ML peaks in PL spectra increased from 0.4 meV for 15 nm well width to 6.2 meV for 1 nm well width. No doublet splitting was observed in PLE spectra. Then, we assigned these two peaks to free excitons and excitons bound to neutral donors. The strong well width dependence of the splitting is well-explained by the well width dependence of the activation energy of donors. This assignment is in good agreement with our previous results of temperature dependent and time resolved PL experiments[2].

PLE showed the Stokes shifts of less than 1meV which is the smallest as far as we know. This small stokes shift indicates the extremely smooth heterointerfaces without microroughness in each ML island.

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LUMINESCENCE FROM n- AND p-TYPE δ-DOPING WELLS IN GaAs: A COMPARATIVE THEORETICAL STUDY

G.M. Sipahi, R. Enderlein, L.M.R. Scolfaro, and J.R.Leite
Instituto de Física da Universidade de São Paulo,
Caixa Postal 66318, 05389-970 São Paulo, S.P., Brazil

Recent experimental photoluminescence (PL) investigations have revealed an interesting puzzle: PL from p-type δ-doping wells turns out to be at least one order of magnitude stronger than that from n-type δ-doping wells having the same sheet-doping concentrations. In this paper we present calculations of PL spectra for both types of wells which confirm this order of magnitude difference and provide PL line shapes in dependence on sample parameters and temperature. The calculations are based on our recently developed method for self-consistent band structure calculations of holes within the 4 x 4 Luttinger-Kohn multi-band envelope function theory [1]. This method is extended to the 8 x 8 Kane Hamiltonian in order to be able to calculate electron band structures and eigenfunctions from the same model as for holes. The radiative recombination probability is calculated for $\mathbf{k}_{//}$-conserving transitions betweeen the lowest electron and heavy or light hole bands by means of the 'golden-rule' expression. The overlap integral between electron and hole envelope wave functions turns out to be the crucial quantity of this expression. The magnitude of this integral differs appreciably for n- and p-type δ-doping wells. In physical terms this may be understood as follows: In both cases the photo-excited minority carriers have to tunnel through the potential barrier caused by the well for the majority carriers. This well is considerably deeper and wider for the electrons of n-type δ-doping samples than for the holes of p-type δ-doping samples, mainly because of the more perfect screening of the ionized dopant sheets by the heavier and thus more strongly localized holes. As a consequence of this, tunneling, and through wave function overlap, also radiative recombination become easier for the photo-excited electrons of p-type samples than for the photo-excited holes of n-type samples. We present self-consistently calculated electron and hole potential wells, band structures and PL spectra for n-type and p-type δ-doping samples in a wide range of doping concentrations. In both types of samples, PL peaks due to transitions into light hole bands are more pronounced than those due to transitions into heavy hole bands. This again may be understood in terms of tunneling.

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SPATIALLY DIRECT RADIATIVE RECOMBINATIONS OBSERVED IN MULTIPLE δ-DOPED GaAs LAYERS

A. Levine, E.C.F. da Silva, L. M. R. Scolfaro, D. Beliaev, A. A. Quivy, R. Enderlein, and J. R. Leite

Instituto de Física da Universidade de São Paulo, C.P. 66318, 05389-970, São Paulo, SP, Brazil

In this work, experimental and theoretical studies of multiple Si δ-doped GaAs layers (Mδ-doped) are reported. Photoluminescence (PL) are measured and compared with results of self-consistent electronic structure (SCF) calculations. A series of samples with different donor concentrations in the δ-doped layer ($N_D = n_D \times 10^{12}cm^{-2}$ with n_D = 1, 3, 5, 7, 9) and a fixed distance between adjacent Si-doped layers (d_s=300Å) was analized. Besides various GaAs related emission structures which arise from the buffer layer, the PL spectra also show bands below (A-band) and above (B-band) the fundamental band edge of GaAs. It can be seen (Fig. 1) that the A-band is strongly dependent on the value of N_D. In order to compare theoretical and experimental results we include the band gap renormalization in the calculation by combining theoretical and experimental values of the cutoff energy. A good agreement between theoretical and experimental data was found and, with this procedure, we could identify the observed emission bands as spatially direct transitions involving electrons associated with the subband structure of the Mδ-doped layers. Contrary to previous reported data, which correlate the A-bands to the superlattice miniband transitions, we have found that they arise from transitions involving localized states of carbon impurities.

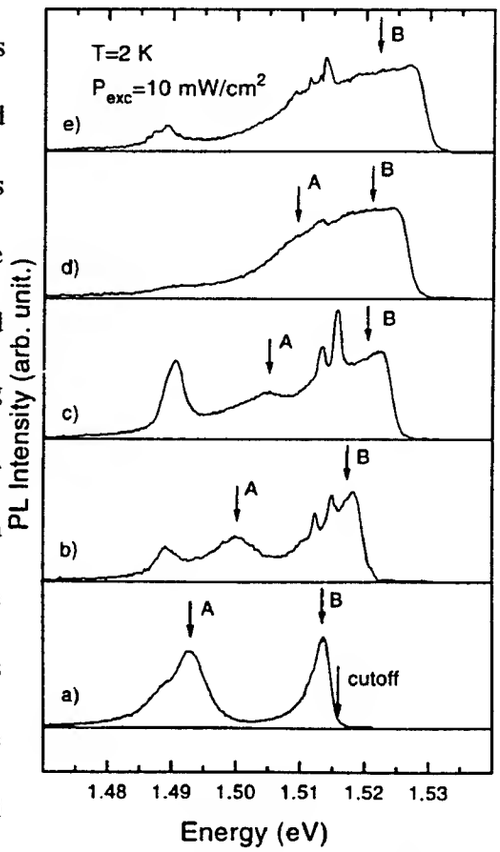

Fig. 1 - PL spectra from GaAs Mδ-doped GaAs layers with doping period d_s=300Å and different nominal donor concentrations: $N_D = n_D \times 10^{12}cm^{-2}$ a) n_D=1, b) n_D=3, c) n_D=5, d) n_D=7, and e) n_D=9.

Evidence for a Metal-Insulator Transition at B=0 in $Si/Si_{0.87}Ge_{0.13}/Si$ Quantum Wells

M. D'Iorio, D. Brown, J. Lam[§], D. Stewart[†], S. Deblois[‡] and H. Lafontaine

National Research Council of Canada, IMS, Ottawa, ON, Canada K1A 0R6
[§]Department of Physics, University of Ottawa, Ottawa, ON, Canada K1N 6N5
[†]Department of Applied Physics, Stanford University, Stanford, CA, USA 94305
[‡]Département de physique, Université Laval, Québec, QC, Canada G1K 7P4

A study of the temperature dependence of the resistivity of gated SiGe quantum well structures has revealed a metal-insulator transition as a function of carrier density at zero magnetic field. Although early scaling theories[1] have argued against the existence of a metal-insulator transition at zero temperature in infinite 2D and 1D systems, more recent theoretical results[2] using a random set of two-dimensional point potentials have shown that such a transition is allowed in two dimensions. Mounting experimental evidence for the metal insulator transition in 2D systems with short range order has accumulated in both semiconducting and superconducting structures[3].

We have studied pseudomorphic, CVD-grown p-type $Si/Si_{0.87}Ge_{0.13}/Si$ quantum wells of various widths (65-200 Å). The samples were gated using a Ti-Au Schottky gate to allow for carrier density variation. Measurement of the transport to quantum lifetime ratio indicates that the transport is dominated by short range scattering. In the temperature range from 25 mK-4.2 K, the temperature dependence shows a transition from a metallic behavior in the high density regime to an insulating phase in the low density regime with a transition boundary close to 2.6×10^{11} cm^{-2}. The scaling properties of the metal -insulator transition will also be discussed..

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Superlattice Vertical Transport with High-Lying minibands

X. L. Lei* I. C. da Cunha Lima† and A. Troper†

* *State Key Laboratory of Functional Material for Informatics, Shanghai Institute of Metallurgy Chinese Academy of Sciences, 865 Changning Road, Shanghai 200050, China*

† *Departamento de Eletrônica Quântica, Instituto de Fisica, UERJ Rua São Francisco Xavier 524, 20550-13 Rio de Janeiro, RJ, Brasil*

Bragg-diffraction-induced negative differential mobility (NDM) in superlattice vertical transpor has attracted much attention in the literature for the past few years. Since the early model suggested by Esaki and Tsu, many calculations have been carried out, using Monte-Carlo simulation, Boltzmann equation and Balance-equation methods. The majority of these theoretical studies, however, were based on the assumption that carriers are moving within a single miniband. Although the basic physical feature of these Bragg-diffraction-related phenomena is included in most single-miniband models, the carrier population of high-lying minibands is not negligible for steady-state transport when the electric field is close to or falls in the NDM regime, where the electron temperature T_e (in equivalent to the energy) can be as high as, or even higher than, the energy distance between the bottoms of the first and second minibands. On the other hand, hot-electron transport in high-lying minibands has already been demonstrated experimentally by injecting carriers of arbitrary energy into semiconductor superlattice. It is thus desirable to pursue a theoretical study on superlattice NDM beyond the lowest miniband model.

The role of high-lying minibands in superlattice vertical transport is investigated in this presentation using a nonparabolic balance-equation approach extended to include multi-miniband occupation. We find that the existence of high-lying minibands results in a decrease of the electron temperature, a reduction of the peak drift velocity and a slow-down of the velocity-drop rate in the negative differential mobility (NDM) regime, in comparison with those predicted by a single miniband model. Numerical calculations of steady-state transport in typical GaAs-based superlattices at room temperature, show that these effects become significant when the strength of the electric field gets close to or falls in the NDM regime. Thus they should be taken into account in a more quantitative analysis of the Esaki-Tsu negative differential conductance.

Influence of Γ-X mixing on carrier transport and photoluminescence in GaAs/AlAs type-I superlattices

N. Ohtani, M. Hosoda, H. Mimura, K. Tominaga, T. Watanabe, and K. Fujiwara*

ATR Optical and Radio Communications Research Laboratories

Hikaridai, Seika-cho, Soraku-gun, Kyoto 619-02, JAPAN

**Department of Electrical Engineering, Kyushu Institute of Technology*

Tobata-ku, Kitakyushu-shi 804, JAPAN

The effects of field-induced X state resonances on carrier transport and optical properties of GaAs/AlAs type-I short-period superlattices (SLs) have been studied. SLs of this type are expected to be used for novel high-speed optoelectronic devices. To confirm the high-speed operation of SL devices, the amount of photo-generated carriers must be quickly swept out from the entire SL, so as not to saturate the optical absorption.

100-period GaAs/AlAs type-I SL samples contained in *p-i-n* diodes were studied. Under ultrashort optical pulse excitation, an anomalously delayed photocurrent (Pc) was observed. Creation of the delayed Pc strongly depends on the reverse bias voltage, independent of the excitation intensity or temperature. When the delayed Pc was observed, the X-valley ground state (X1) in the AlAs barrier is resonantly located closer to the Γ-valley second state (Γ2) in the adjacent GaAs well; X1-Γ2 mixing. Under cw laser excitation, we could also observe a Γ2-hh1 PL due to the X1-Γ2 mixing. The Γ2-hh1 PL behaviors imply that a number of electrons trapped in X1 can resonantly tunnel to Γ2 because of the X1-Γ2 mixing. For three SL samples with GaAs/AlAs widths of 24ML/5ML, 24ML/6ML, and 22ML/12ML, it is confirmed that the delayed Pc and the Γ2-hh1 PL appear when the X1-Γ2 mixing occurs. These observations clearly suggest that the delayed Pc component and the Γ2-hh1 PL arise from the electrons tunneling through the X1-Γ2 path in the SLs, and demonstrate that electrical and optical properties even in type-I SLs are frequently affected by X states in the applied electric field.

Resonant Γ-X-Γ Tunnelling in GaAs/AlAs/GaAs Single Barrier Heterostructures at Zero and Elevated Magnetic Field.

J.J.Finley†, R.Teissier‡, M.S.Skolnick†, J.W.Cockburn†, R.Grey§, G.Hill§, M.A.Pate§.

† Department of Physics, University of Sheffield, Sheffield, S3 7RH. U.K.

§ EPSRC Central Facility, Department of Electrical Engineering, University of Sheffield, Sheffield S3 7JD, U.K.

‡ CNRS Laboratoire de Microstructures et Microelectronique, 92225 Bagneux Cedex, France.

We present the results of a magneto-transport study of the Γ-X-Γ tunnelling process in a range of GaAs/AlAs/GaAs p-i-n heterostructures. These measurements represent the first unambiguous spectroscopic determination of the nature and role of intervalley Γ-X transfer in transport through AlAs/GaAs heterostructures.

When forward biased at zero magnetic field (B=0) pronounced structure is observed in the differential conductance-bias (σ_d-V) characteristics of all samples. Such structure is identified as arising from resonant Γ-X transfer via quasi-bound electronic states in the AlAs layer derived from the X point of the Brillouin zone. We find confined states arising from both the transverse (X_{xy}) and longitudinal (X_z) X valley conduction band minima contribute strongly to the tunnelling current. The precise Γ-X transfer mechanism is found to depend strongly upon the nature of the X state involved. For Γ-X_z transfer the transfer is principally elastic whereas for Γ-X_{xy} transfer inelastic processes are found to dominate. Detailed modelling of the shape of the resonances observed in σ_d-V enables us to obtain quantitative values for the scattering rates for each Γ-X transfer channel. The nature of the Γ-X_z transfer is studied further by application of B field (||I up to 14T). For B>0T pronounced periodic structure is observed in σ_d-V which arises from inter-Landau level (LL) elastic transfer between Γ symmetry LLs formed in the 2D emitter and X symmetry LLs in the AlAs layer derived from the lowest X_z confined state. Strong features corresponding to LL index conserving ($\Delta v=0$) transfer are observed in addition to weaker non-conserving ($\Delta v\neq 0$) transitions. Since the Γ-X_z inter LL transfer involves 0D states characterised by different effective masses, structure reflecting two distinct frequencies are found in strong contrast to the behaviour for conventional Γ-Γ tunnelling. For $\Delta v=0$ transfer, structure with a splitting proportional to the difference in the cyclotron frequencies $\left(\omega_c^{\Gamma} - \omega_c^{X}\right)$ is observed, whilst for $\Delta v\neq 0$ transitions the lower frequency corresponding to ω_c^{X} is reflected. Analysis of these features enables the transverse (X_{xy}) effective mass in AlAs to be determined and permits us to reach quantitative conclusions about the importance of $k_{\|}$ conservation in the elastic Γ-X_z transfer process.

Γ to X_z electron transfer times in type-II GaAs/AlAs superlattices due to emission of confined and interface phonons

Gerald Weber* **and Ana M. de Paula+**
**Grupo de Física dos Sólidos e Eletrônica Quântica, Instituto de Pesquisa, Universidade São Francisco, 13251-900 Itatiba SP, Brazil*
+Instituto de Física, Universidade Estadual de Campinas, Caixa Postal 6165, 13083-970 Campinas SP, Brazil

Carrier dynamics in semiconductor heterostructures has attracted considerable attention in the last few years due to its importance to both fundamental physics and device applications. The hot carrier relaxation in type-I quantum wells and superlattices is reasonably well understood, yet there is little understanding of the carrier dynamics in type-II superlattices.

In AlGaAs-AlAs superlattices the Γ states in the AlGaAs layers can be made higher in energy than the X states in AlAs layers by an appropriate choice of Al concentrations and layer thicknesses. Thus, the superlattice becomes indirect in real space, i.e., a type-II superlattice. Furthermore, the bulk X_z valley folds onto the Γ_{SL} point of the superlattice minizone while the $X_{x,y}$ valleys fold onto the M_{SL} point [1] and the superlattice will be direct in the reciprocal space, except when the $X_{x,y}$ valleys are lower in energy than the X_z valley [2].

We calculate the $\Gamma \rightarrow X_z$ electron transfer times due to the emission of optical phonons in type-II GaAs-AlAs and AlGaAs-AlAs superlattices extending our previous calculations [3] by including interface phonon modes. A dielectric continuum model is employed to describe the electron-phonon interaction and the electron envelope wave functions are obtained from a Kronig-Penney model. The calculated transfer times are in good agreement with available experimental results [4, 5].

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High-field transport in superlattices: observation of the Stark-Cyclotron Resonance

Luca Canali[1], Marco Lazzarino[2], Lucia Sorba[2], and Fabio Beltram[1,2]

1. Scuola Normale Superiore and INFM, I-56126 Pisa, Italy
2. Laboratorio TASC dell'INFM, I-34012 Trieste, Italy

We shall present the first observation of the Stark-cyclotron resonance (SCR) in a semiconductor superlattice (SL). At SCR the potential drop per period is an integer multiple of the magnetic quantization energy and elastic tunneling transport between Landau levels becomes possible. Unambiguous demonstration of SCR will be given for transitions involving up to four Landau-level index changes.

In the presence of strong electric and magnetic fields parallel to the growth axis each SL miniband breaks down into a set of discrete Wannier-Stark-Landau (WSL) levels. These are given by $\mathcal{E}_{n,\nu} = \mathcal{E}_{0,0} + (eFd)\nu + \hbar\omega_c(n+1/2)$, where e is the electronic charge, F is the electric field, d is the SL period, $\omega_c = eB/m^*$ is the cyclotron frequency ($\nu = 0, \pm1, \pm2, \ldots$ and $n = 0.1.2\ldots$ are the well and Landau indices respectively). In this regime because of the field-induced localisation current in the SL generally proceeds by hopping between WSL states of neighboring periods. When WSL states (ν, n) and $(\nu', n+\delta n)$ have the same energy for integer values of δn, however, resonant transport can be made accessible by elastic scattering with impurities and interface roughness. The increased conductivity determined by the additional transport channel is the manifestation in transport of SCR.

In an appropriately designed AlGaAs/GaAs heterostructure current-voltage characterization will be shown in the temperature range from 0.3 to 200 K with magnetic fields up to 9.2 T. Current resonances have been observed at particular bias and magnetic field values. A fan chart of these quantities at resonance shows that experimental points align along four distinct straight lines as expected for transitions involving $\nu' = \nu + 1$ and $\delta n = 1.2.3$ and 4 Landau level transitions.

INVESTIGATIONS OF BAND NON-PARABOLICITIES IN STRAIN-BALANCED GAINAS/GAALINAS COUPLED QUANTUM WELLS

R.W. Martin*, F. McGow*, M. Hopkinson†, J.P.R. David†.

*Dept. of Physics and Applied Physics, Strathclyde University, John Anderson Building, 107 Rottenrow, Glasgow, G4 ONG.

†EPSRC III-V Semiconductor Facility, Dept. of Electronic and Electrical Engineering, University of Sheffield, PO Box 600, Mappin St., Sheffield S1 3JD.

The large non-parabolicities that exist in both the conduction and valence bands of GaInAs/GaAlInAs multi quantum wells (MQW) are very dependent on the degree of strain within the structure. Such effects have been investigated using magneto-spectroscopy on a series of strain-balanced, coupled MQW grown by Molecular Beam Epitaxy. With magnetic field applied perpendicular to the sample, absorption spectra reveal Landau level transitions up to energies greater than 400meV above the zero-field transition. Comparison of calculated Landau level energies with the observed transitions provides detail of the band non-parabolicities and these are investigated as a function of strain. In addition, as the Landau level transition energy increases large changes in the heavy hole in-plane mass may be demonstrated and are shown to be associated to energy-dependent coupling with the light hole confined states. The energies of the light hole, and higher excitons, are most clearly identifiable in absorption data with high parallel magnetic fields and are modelled using envelope function calculations. Effects of the considerable inter-well coupling are included and will be shown to lead to important consequences for devices based on electroabsorption in such MQW.

A STUDY OF GaInP-GaAs INTERFACES : METALLURGICAL COUPLING OF SUCCESSIVE QUANTUM WELLS

O. Schuler, O. Dehaese, X. Wallart and F. Mollot

Institut d'Electronique et de Microélectronique du Nord UMR CNRS 9929

BP69, 59652 Villeneuve d'Ascq Cédex, FRANCE

Lattice matched GaInP on GaAs is a possible substitute for AlGaAs, particularly when the valence band offset has to be maximised, as for Heterojunction Bipolar Transistors (HBT). It appeared that a good control of the interface quality was much more difficult than for GaAs-AlGaAs, or even than for InGaAs-InP, which nevertheless presents the same double commutation of III and V elements.

We present here a study of these interfaces by means of photoluminescence (PL) of GaAs multi quantum wells (MQW), all embedded in GaInP, or asymmetric wells GaInP-GaAs-AlGaAs. Asymmetric structures allow to disconnect the two types of GaAs-GaInP interfaces by changing the order of the growth sequence, supposing that GaAs-AlGaAs interfaces are nearly perfect, at least when compared with GaInP-GaAs ones.

A series of samples has been grown by Gas Source MBE. The PL energies of quantum wells were compared with calculations based on transfer matrix envelope function approximation, well suited for asymmetric structures. An AlGaAs-GaAs-AlGaAs structure was grown as a reference.

The GaInP-GaAs-AlGaAs MQW structures (GaInP grown first) are in good agreement with calculations. The reverse ones, AlGaAs-GaAs-GaInP, present a lower PL energy than calculated. It has not been possible to relate this discrepancy to the element commutation sequences at the interface. But, very astonishingly, we recover the agreement with theory on single QW samples, or in MQW when the GaInP thickness was increased up to 100 nm. We first have shown this could not be an electronic coupling between QW. We interpret this phenomenon as a diffusion of As atoms through the GaInP barrier, from the next GaAs acting as an As source. As atoms exchange with P atoms at the GaAs-GaInP interface of the former well, leading to a small gap strained InGaAs region shifting PL to a lower energy.

Polariton-Atom Bound State in Dispersive Medium: Application to III-V semiconductors.

M. Singh and V. I. Rupasov
Department of Physics, University of Western Ontario,London, Ontario,Canada N6A 3K7.
Landau Institute, Moscow, Russia.

It has been shown that the existence of energy gap in PBG materials give rise to such interesting and intriguing phenomena such as photon-atom bound states[1]. But, it is well known also that a energy gap for propagating electromagnetic modes exists in many natural dielectrics and semiconductors. In contrast to PBG materials, a gap in these media is caused by photon coupling to an elementary excitation (optical phonon) of the medium . The "normal" electromagnetic modes in frequency dispersive media (DM) are determined by the Maxwell equations with a frequency-dependent dielectric permeability and are treated as "photons in a medium" (or "polaritons"). Their spectrum consists of two branches of allowed states separated by a gap in which propagating polariton modes are completely forbidden. Therefore, the intriguing question arises of whether quantum optical phenomena predicted for PBG materials are observed in dispersive media.In this paper we report some first results of quantum electrodynamics of polaritons interacting with a single two-level atom whose resonance frequency lies near a polaritonic gap of DM. Within the framework of the conventional dipole resonance (rotating wave)approximation, we diagonalize exactly the Hamiltonian of the field + medium + atom system. We show that the system's spectrum contains both two continues branches corresponding to propagating polariton modes scattered on the atom and a single discrete mode whose eigenfrequency lies within the polaritonic gap. This novel discrete mode can be treated as a polariton-atom bound state in which the atomic excitation is dressed by the radiation field and the medium polarization which are localized in the vicinity of the atom. To clarify the role of the bound state in quantum optical phenomena in DM, we solve the problem of spontaneous decay of an initially excited atomic state and show that the existence of the polariton-atom bound state leads to a significant suppression of the spontaneous emission process. Theory is applied to GaAs and GaSb semicondcutors.[1] S. John, Phys. Rev. Lett. 58, 2486 (1987).

Nonequilibrium optical phonon distribution function in double-barrier *GaAs/AlAs* quantum well

V. V. Mitin, N. A. Bannov, and G. Paulavičius

Department of Electrical and Computer Engineering

Wayne State University, Detroit, MI 48202

We have studied nonlinear coupled transport of 2D electrons and confined optical phonons in *GaAs/AlGaAs* quantum well in a wide range of the lattice temperatures and applied electric fields. Self consistent Monte Carlo technique has been used to solve the coupled kinetic equations for the electrons and optical phonons in the structure.

The average time of optical phonon emission by electrons (0.15 *ps*) is approximately fifty times shorter than the average time of the optical phonon decay into short wavelength acoustic phonons (7 - 8 *ps* for *GaAs*). This substantial difference in the generation/decay times as well as the confinement inside the heterostructure lead to a significant growth of the nonequilibrium optical phonon population accumulated by the heated electron gas. An additional mechanism which controls the optical phonon population and the mean electron energy is the optical phonon reabsorbtion by the 2D electrons.

We have obtained that when the optical phonon accumulation is significant, it is accompanied by the narrowing of the optical phonon distribution and substantially affects the 2D electron transport properties. We have formulated the conditions when nonequilibrium phonons not only rise the mean 2D electron energy but dramatically increase the carrier mobility as well.

RAMAN STUDY OF CONFINEMENT OF OPTICAL PHONONS IN GaAs QWWs ON FACET (311)A GaAs.

V.A.Volodin, M.D.Efremov, V.Ya.Prints, V.V.Preobrazhenskii, B.R.Semyagin
Institute of Semiconductor Physics, Novosibirsk, Russia

The lateral superlattices (LSLs) GaAs/AlAs with ultrathin GaAs layers have been grown using MBE technique on (311)A GaAs surface with buffer layers of GaAs and AlAs. The average thickness of GaAs layers was varied for different LSLs from 21 to 8.5Å, the average thickness of AlAs was 27Å for all LSLs. Surface (311)A GaAs is stepped by nanofacets with lateral period 32Å, but its height is discussed to be 10.2 or 3.4Å from high resolution TEM and scanning tunneling microscopy data correspondingly. Reducing the thickness of GaAs in the process of heteroepitaxial growth of GaAs and AlAs can lead to transformation of GaAs layer into array of quantum wires. Strong damping of GaAs-like optical phonons in surrounding AlAs leads to confinement of them in GaAs. The Raman study of longitudinal confined phonon and influence of both thickness and periodic corrugation of GaAs layer have been carried out.

For the samples with relatively thick GaAs layers (15Å and thicker) the dispersion of confined phonons was like dispersion of phonons confined in layers of GaAs in (100) oriented superlattic. For the samples with average thickness of GaAs layers 11.3Å and thinner, the strong difference in behaviour of phonons confined in (311)A LSL from dispersion of phonons confined in (100) SL was observed. So, instead of decreasing of confined phonons frequency with thinning of GaAs layer, as it had been observed everywhere for (100) SLs, a sharp increasing of its frequency have been observed. This increasing can be explained as result of jointing of AlAs facets and forming of rigid barriers for GaAs-like optical phonons in lateral direction. This leads to quantization of optical phonons in GaAs quantum wires, in this case phonons are localized in direction along its quasiimpuls plus also in perpendicular direction, and its frequency increases.

Calculation of phonon frequencies in the model of two dimensional chains was carried out and the obtained results are in good agreement with experimental data. From our data one can resume that the jointing of AlAs facets takes place when the average thickness of GaAs layer was thinner than 15Å. This supports the model in which the height of facets on corrugated surface (311)A GaAs is 10.2Å.

Using selection rules for (311) oriented surface, the transverse optical phonons with phonon polarizations along and transverse to quantum wires have been observed in various geometries of Raman scattering. Splitting of TO phonons of two different polarizations was observed. This splitting is resulted of (311)A surface corrugation and confirms the formation of GaAs quantum wires in the studied structures.

Infrared Induced Intrasubband Transitions Effect on the Raman Spectrum of III-V semiconductors

M. Bendayan[a], R. Kapon[b], R. Beserman[a], A. Sa'ar[b] and R. Planel[c]

[a] Solid State and Physics departement, Technion—Israel Institute of Technology, Haifa 32000, Israel

[b] Division of Applied Physics, School of Applied Science, The Hebrew University of Jerusalem, Jerusalem 91904, Israel.

[c] Laboratoire de Microélectronique et de Microstructures—CNRS, 196 Avenue H. Ravera 92220 Bagneux, France

We present an experiment in which the Raman spectrum of an asymetric doped GaAs-AlGaAs quantum well was studied under resonant CO_2 laser excitation. We show that the CO_2 laser induces a photogenerated electrons—LO-phonon coupling.

The sample consists of 25 periods of modulation doped quantum well structure. Each period consists of GaAs, followed by 70 Å $Al_{0.2}Ga_{0.8}As$, followed by 50 Å GaAs; each structure is separated from the next by 450 Å of $Al_{0.4}Ga_{0.6}As$. Carriers are provided by a thin GaAs (30 Å) well in the center of the $Al_{0.4}Ga_{0.6}As$ region, n-doped at $4.10^{11}\,cm^{-2}$ with Si.

Our calculation shows that the first energy level is localized in the 70 Å well whereas the second is localized in the 50 Å well. All higher subbands are spread across the full width of the structure. The sample was designed such that the energy difference between the first and third levels correspond to the 9.6 μm CO_2 laser wavelength. This allows pumping of the carriers from the first localized subband to the third delocalized one, thus providing a photoinduced space charge distribution.

This space charge distribution causes a change in the Raman spectra of the LO-phonons by the Frölich interaction. Under CO_2 laser pumping, the peak intensities corresponding to the GaAs-like phonon modes are different from the non-excited case. This effect was seen to be CO_2 wavelength and polarization dependent indicating that it comes from the intersubband absorption.

Interface Roughness Broadening of Intersubband Transitions

K. Campman*, H. Schmidt, A. Imamoglu, A. Gossard
Department of Electrical and Computer Engineering
University of California, Santa Barbara, CA 93106
* email: 6500klc@ucsbuxa.ucsb.edu
phone: (805) 893-8154 fax: (805) 893-8486

With the recent development of an intersubband laser[1] and the proposal of a new class of optical devices based on quantum interference between intersubband transitions in semiconductor quantum wells[2], the understanding and control of the dynamics of intersubband transitions has become critical. Unwanted broadening of the transition lineshape can have adverse effects on the performance of quantum well optical devices. Due to improvements in growth techniques, the linewidths achievable in MBE grown quantum wells have declined since the first observation of an intersubband transition, with the ultimate lower limit set by phonon lifetime broadening. In this work, we examine the mechanisms responsible for the broadening of intersubband transitions and their relative importance in determining linewidth.

We have performed intersubband absorption measurements in single quantum wells of different well widths and alloy compositions. One series of samples consisted of four modulation doped $Al_{0.3}Ga_{0.7}As/GaAs$ quantum wells grown consecutively differing only in the width of the quantum well (70, 80, 90, 105 Å). Absorption spectra measured at 4.2K show strong absorption peaks (20-30%) in the mid-IR with Lorentzian lineshapes. The linewidth (FWHM) was found to decrease monotonically from 4.4 meV to 2.5 meVas the well width is increased from 70Å to 105Å. This behavior is consistent with broadening dominated by interface roughness from the monolayer fluctuations typically present at MBE grown interfaces. For all samples measured the linewidth is found to remain constant as electrons are depleted from the well by the application of a gate bias. This is again consistent with interface roughness since electrons would be relatively ineffective in screening the well width fluctuations. The observed trend in linewidth is opposite to that expected for lifetime broadening due to optical phonons. For scattering by optical phonons, we would expect that wider wells would lead to decreased transition energy, shortened phonon lifetime, and broader absorption lines.

Another series of samples was grown with fixed quantum well width (100Å) and with differing alloy content in the well ($Al_{0.05}Ga_{0.95}As$, GaAs, $In_{0.05}Ga_{0.95}As$, $In_{0.1}Ga_{0.9}As$). The mobility in these structures is found to degrade strongly as Al or In is added to the quantum well, as expected for alloy-disorder scattering. The linewidth of the absorption peak, however, is found to remain relatively narrow for all alloy compositions. This indicates that addition of In or Al can be used to lower or raise quantum well energy levels without resorting to narrow quantum wells where interface roughness severely broadens the intersubband transition.

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INTERSUBBAND LIFETIME IN A COUPLED-QUANTUM WELL WITH $\Delta E < \hbar\Omega_{LO}$: TIME-RESOLVED AND STEADY-STATE MEASUREMENTS

J.N. Heyman[1], K. Unterrainer[2], K. Craig[3], J. Williams[3], M.S. Sherwin[3], K. Campman[4], P.F. Hopkins[4], A.C. Gossard[4], B.N. Murdin[5], C.J.G.M. Langerak[5]

[1]Department of Physics and Astronomy, Macalester College, St. Paul, MN 55105.
(fax:+1 612 696 6432; email: heyman@macalstr.edu)
[2] Institut für Festkörperelektronik und Mikrostrukturzentrum, TU-Wein, Floragasse 7, A-1040 Wein.
[3]Department of Physics and Center for Free Electron Laser Studies, UCSB, Santa Barbara, CA 93106.
[4]Materials Department, UCSB, Santa Barbara, CA 93106.
[5]FOM-Institute "Rijnhuizen", P.O.Box 1207, NL-3430 BE Nieuwegein, The Netherlands

Reported values of the intersubband lifetime (T_1) in quantum wells with subband spacing $\Delta E < \hbar\Omega_{LO}$ range between *40ps - 1.2ns*. We show that both time-resolved and steady-state techniques yield consistent T_1's when applied to the same coupled-quantum well sample. Pump-probe measurements[1] were performed at the Free Electron Laser for Infrared eXperiments (FELIX) at Rijnhuizen, the Netherlands. T_1 was determined both from measurements of the intersubband absorption as a function of delay between *10ps* pump and probe laser pulses, and from measurements of an intersubband-transition-induced photovoltage as a function of delay between pulses. In steady-state measurements[2] performed at the UCSB Free Electron Laser, the excited-subband population was measured from the photovoltage under quasi-CW FIR laser excitation at the intersubband transition frequency. As the generation rate was known from the absorption cross section and the laser intensity, the relaxation rate could be found.

Time-resolved measurements yielded lifetimes of $T_1 = 0.4ns$ *to* $T_1 = 1.1ns$ under different conditions, longer than the calculated upper limit to the lifetime due to acoustic-phonon scattering (*250ps*) for this structure. These results agree with steady-state measurements performed at laser intensities $\leq 1\ W/cm^2$. However, steady-state measurements give shorter T_1*'s* at high laser intensities, while pulsed measurements yield T_1 's which are nearly independent of pulse energy. This suggests that laser-heating effects (such as thermally-activated optical phonon scattering) dominate relaxation at high CW intensities.

Steady-state measurements of T_1 can be performed at sub-milliwatt laser intensities, which is advantageous for low-temperature studies. Currently we are using a CW FIR laser to study intersubband relaxation at low temperatures (*2-10K*). Although the acoustic phonon intersubband scattering rate is expected to vary only weakly with lattice temperature in this regime, preliminary measurements show a strong temperature dependence to the intersubband lifetime.

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ELECTRO-OPTICAL PHENOMENA ACCOMPANYING ELECTRON AND HOLE HEATING IN SUPERLATTICES AND QUANTUM WELLS GaAs/AlGaAs AND Ge/GeSi

L.E.Vorobjev[†], S.N.Danilov[†], E.A.Zibik[†], D.A.Firsov[†], V.A.Shalygin[†], A.Ya.Shick[‡], I.I.Saidashev[‡], A.Ya.Aleshkin*, O.A.Kuznetsov*, L.K.Orlov*

[†]St.Petersburg State Technical University, Politechnicheskaya 29, St.Petersburg 195251, Russia.

[‡]Ioffe Physico-Technical Institute RAS, St.Petersburg, Russia

*Institute for Physics of Microstructures RAS, N.Novgorod, Russia

Results of experimental and theoretical investigations of the new optical phenomena connected with intersubband transitions of hot electrons and holes in quantum wells (QW) and superlattices (SL) in longitudinal electric field are presented.

Absorption of CO_2-laser radiation due to intersubband transitions of hot electrons and holes in selectively and non-selectively doped n-type GaAs/AlGaAs QW and SL and in p-type Ge/GeSi QW was investigated. The different mechanisms of influence of longitudinal electric field on light absorption coefficient were suggested for two types of n-QW. In both cases carrier heating causes the change of energy spectrum and consequently the change of light absorption. In selectively doped QW change of energy spectrum is determined mainly by the change of space charge in the structure at electron heating in longitudinal electric field. The change of energy spectrum in non-selectively doped QW is caused by the change of exchange interaction with increase of average electron energy. The role of depolarization phenomena and energy band non-parabolicity is also discussed. The equilibrium absorption spectra and electric field dependencies of absorption coefficient for two light polarizations are presented.

Results of investigations of light absorption due to direct transitions of hot holes between bound states and continuum in Ge/GeSi MQW and their discussion are presented.

The birefringence under heating of electrons and holes by electric field is found in n-type GaAs/AlGaAs and p-type Ge/GeSi QW. The mechanism of this phenomenon is suggested.

Polarization dependent intersubband absorption and normal-incidence infrared detection in p-type Si/SiGe quantum wells

P. Kruck, A. Weichselbaum, M. Helm, T. Fromherz, G. Bauer
Institut für Halbleiterphysik, Universität Linz, A-4040 Linz, Austria
J.F. Nützel, G. Abstreiter
Walter Schottky Institut, TU München, D-85784 Garching, Germany

For p-doped quantum wells the band mixing in the valence band allows intersubband transitions for light polarized both parallel and perpendicular to the growth direction. In contrast to n-type quantum well infrared photodetectors (QWIPs), in p-type material normal-incidence detection can be achieved without the need for special optical coupling schemes. Furthermore Si/SiGe QWIPs offer the additional advantage of being compatible with standard Si processing electronics.

Here we present a detailed study of the polarization dependence of subband absorption and photoconductivity in Si/SiGe quantum wells. In the absorption experiment the samples consist of 30 $Si_{0.65}Ge_{0.35}$/Si quantum wells with a thickness of 25Å separated by 150Å barriers. The p-doping gives a sheet carrier concentration of $p_S=2.8 \times 10^{12}cm^{-2}$ per layer. Both p- and s-polarized absorption is observed. The spectra agree well with the theoretical results of a self-consistent Luttinger-Kohn band-structure calculation [1], which also enables unambiguous identification of all involved transitions.

In the detector structures the active region is embedded between two heavily p-doped contact layers. The barrier thickness is increased up to 300Å to reduce the dark current. Detector mesas were fabricated by photolithography and reactive ion etching (RIE). Unexpectedly, the photoresponse is higher in s-polarization than in p-polarization (in contrast to the absorption), which is favorable for normal-incidence detection. This behavior demonstrates the importance of the vertical transport properties of the photoexcited carriers.

For a detector with cut-off wavelength of 8 μm we measure normal-incidence current responsivities of 80mA/W. Due to the low dark current, background-limited infrared performance (BLIP) is achieved at T=80K for low bias. Furthermore we will report on noise measurements and evaluate the detectivity, D^*.

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Broad-band microwave detection with a novel 2-D hot-electron device

Stefano Barbieri, Francesco Mango, and Fabio Beltram - *Scuola Normale Superiore, Piazza dei Cavalieri, 7, I-56126 Pisa, Italy.*
Marco Lazzarino and Lucia Sorba - *Laboratorio Tecnologie Avanzate, Superfici e Catalisi dell'Istituto Nazionale di Fisica della Materia, Padriciano, 99, I-34012 Trieste, Italy.*

We present the operation of a new multiquantum well hot-electron microwave detector. The working principle of this device is based on the interaction of two-dimensional free carriers inside the wells with the in-plane electric field. Absorbed radiation increases the carrier temperature thereby enhancing thermionic current through the heterostructure to which a dc voltage is applied. This detector was realized with an AlGaAs heterostrutcture grown by molecular beam epitaxy on an undoped GaAs substrate. It consists of 20 periods of n-doped 4.5-nm thick GaAs quantum wells separated by 30-nm undoped $Al_{0.3}Ga_{0.7}As$ barriers sandwiched between doped GaAs layers to which contacts were provided. The nominal parameters of the structure were verified by direct measurement of the conduction-band discontinuity via current-voltage characterization. We shall report room-temperature responsivity of several 10^3 V/W, comparable to that of conventional solid-state devices (e.g. Schottky-barrier based detectors). The different physical principle of operation, however, yields for the present detector a broader frequency range, extending up to the submillimeter band, and short response times which can be estimated around 10 ps. The temperature dependence of the responsivity will be presented. Furthermore, from noise measurements, we obtain a noise equivalent power comparable to that of present state-of-the-art devices. The dependence of the responsivity on the angle θ between the quantum-well plane and the electric field of the incident radiation will be presented and discussed. We shall show that the photocurrent is proportional to $\cos^2\theta$ consistently with the principle of operation. Finally from the measured photocurrent we could estimate the increase of the electron temperature which turned out to be of the order of a few K. With the help of an energy-balance model we calculated the expected temperature variation. The role of the high static electric field will be discussed.

ELECTRO-ABSORPTION MODULATOR USING A TYPE II QUANTUM WELL IN THE $In_XGa_{1-X}As/InP$ SYSTEM

C.LUGAND, T.BENYATTOU, G.GUILLOT
LPM (UMR CNRS 5511), INSA-Lyon, Bât.502, F-69621 Villeurbanne cedex

T.VENET, M.GENDRY, G.HOLLINGER
LEAME (UMR CNRS 5512), Ecole Centrale de Lyon, F-69131 Ecully cedex

$In_xGa_{1-x}As/InP$ system is very interesting for devices working in the 1.55 μm spectral range for optical telecommunication and allows both the growth of tensile and compressively strained layers. $In_xGa_{1-x}As/In_{0.53}Ga_{0.47}As$ structure elaborate on InP substrate is expected to show a type II band line-up for the light hole (LH) valence band due to the tensile strain. Thanks to the dipole that originates from the spatial separation of electrons and holes, type II heterostructures promise to exhibit a linear Stark shift instead a quadratic one for type I QW with both blue and red shift that could be used in an electro-optical modulator.

Photoluminescence measurements at low temperature under different excitation power were carried out on InGaAs tensile strained (x=0.3) quantum well with InGaAs barrier lattice matched to InP. Evidence of a type II recombination was found between carriers confined in the tensile layer and in the lattice matched one. This study allows us to propose a precise determination of the light holes band off-set in the $In_{0.3}Ga_{0.7}As/ In_{0.53}Ga_{0.47}As$ system.

Moreover we propose to include the previous structure in AlInAs barrier in order to confine both electrons and holes as the intrinsec layer of a PIN diode for light modulator applications. To simulate the optical behaviour of such a structure under electric field we solved the Schrödinger equation using the envelope function approximation and simulate the absorption spectrum. As expected the type II structure presents a strong Stark effect and for small biases a linear shift is observed. These features are confirmed by optical characterization of this structure. We will show the interest of such device for optical modulator using Stark effect.

Photodiffraction in GaInAs/GaInAsP MultiQuantum Wells

R. Grac, M. Pugnet, J.H. Collet
Laboratoire d'Analyse et d'Architecture des Systèmes du CNRS
7 av. du Colonel Roche,F-31077 Toulouse Cedex, France

B. Lambert, C. De Matos, H. L'Haridon, A. Le Corre
France Telecom CNET/LAB, Technopole Anticipa2,
route de Trégastel, 22307 LANNION Cedex, France

Abstract

We report new results on the diffraction properties of photoinduced gratings in GaInAs/GaInAsP MQW structure. This structure was grown by a gas source molecular beam epitaxy. It consists of 211 periods of 7nm GaInAs quantum wells separated by 9nm GaInAsP barriers. After epitaxial lift-off, the structure was grafted by Van der Waals bonding onto a gold coated sapphire substrate. The excitonic absorption peak of the QWs is about 1.55 μm. The original feature of this device is that QWs are enclosed in an assymetric Fabry-Pérot microcavity. The back and front reflectivities have respective values of 0.99 and 0.2. Gratings are created by absorption at 1.064 μm. The confinement of light in the cavity leads to oscillations of the diffraction efficiency in the [1.35-1.65 μm] wavelength range. Those oscillations are observed by picosecond time-resolved diffraction spectroscopy. This effect may be simply considered as an increase, at the resonance, of the effective thickness of the photogenerated gratings due to the many round trips of light in the cavity. Experimental data are compared to diffraction calculations in microcavities based on coupled wave theory [1]. At a probe wavelength of 1.55 μm, the diffraction efficiency increases at low excitation intensities, saturates at a pump energy about 360 $\mu J/cm^2$ and decreases at pump energies higher than 400 $\mu J/cm^2$. This phenomenon is accounted for by an absorption saturation at high excitation involving a deacrease of the carriers density contrast of the bright and dark interference fringes. The maximum input diffraction efficiency at a wavelength of 1.55 μm is equal to 2.5 %.

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Electro-Optic Effects in GaAs/AlGaAs Parabolic Quantum Well Structures

W. Geißelbrecht, A. Masten, O. Gräbner, M. Forkel, G.H. Döhler
Institut für Technische Physik, Universität Erlangen-Nürnberg, Germany

K. Campman, A.C. Gossard
Materials Department, University of California, Santa Barbara, USA

By varying the ratio of the layer thicknesses in GaAs/AlGaAs short period superlattices it has become possible to synthesize semiconductor structures with a nearly parabolic potential profile (digital growth mode during MBE fabrication). An electric field applied in growth direction of such parabolic quantum well (PQW) structures results in quadratically decreasing optical transition energies for the various interband subband transitions („Parabolic Stark Effect") as well as in a systematic modulation of their oscillator strengths. This modulation is due to the alternately constructive and destructive overlap of the electron and hole envelope wavefunctions, which spatially shift in opposite direction with increasing electric field. This behavior finally leads to electroabsorption spectra exhibiting a superposition of red-shifting steps that arise from the discrete interband subband transitions with a fan of blue-shifting „parabolic Franz-Keldysh oscillations" that evolve from the bandgap energy corresponding to the center of the PQW. Thus, the electroabsorption of PQW structures resembles the recently observed coexistence of Wannier-Stark ladder transitions and Franz-Keldysh oscillations in the electroabsorption of GaAs/AlAs superlattice structures with broad minibands.

We report on a systematic experimental and theoretical investigation of the electroabsorption in GaAs/AlGaAs PQW structures. In our experiments, we performed transmission, reflectance and photocurrent measurements using a sensitive double modulation technique. The measurements were carried out on p-i-n-diode type PQW samples with different well widths. In samples with a narrow PQW, the discrete structure of the interband subband transitions can be resolved in the electroabsorption spectra. In samples with a wider PQW (and therefore a smaller subband spacing), these transitions can no longer be resolved individually due to the broadening. Their superposition, however, results in a red-shifting, quasi-linear pattern in the electroabsorption spectra, which is modulated by the blue-shifting, non-linear fan of the „Parabolic Franz-Keldysh Effect". The experimental results are in good agreement with calculated single-particle absorption spectra based on a simple harmonic oscillator model.

PHOTONIC CRYSTAL MADE BY CLOSE PACKING SiO_2 SUBMICRON SPHERES

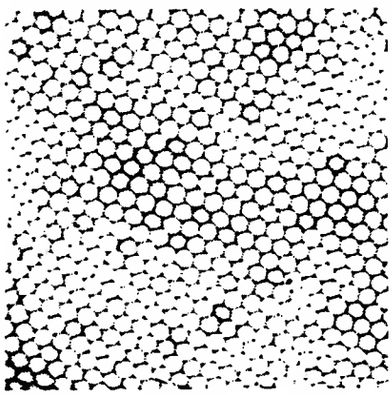
C. López, H. Míguez[(†)], L. Vázquez, F. Meseguer, R. Mayoral and M. Ocaña

Instituto de Ciencia de Materiales (CSIC), Cantoblanco 28049 Madrid Spain
Tel/Fax: intl.+34·1·3349019/3720623; e-mail: cefe@vm1.sdi.uam.es
[(†)]Instituto de Tecnología Química (CSIC-UPV), 46022 Valencia Spain

Photonic crystals have gathered great importance both from pure and applied physics point of view.[1] In the present work we show that monodisperse silica microspheres packed in a solid structure can be used as a means to produce 3D periodic dielectric materials, similar to opals, that can behave as photonic crystals.

Hydrolysis of Si alcoxide and later polymerisation of Si-O chains, following the Stöber-Bohn-Fink method[2], was used to obtain spherical microparticles. Appropriate reaction conditions allow us to obtain perfect spherical microparticles with very small dispersion in diameter. A wide range (0.3 to 0.65 μ) of particle size is achievable through a strict control of the reaction parameters. The monodisperse suspensions were charaterised by Transmission Electron Microscopy.

The method used to obtain a crystalline solid dielectric structure from the colloidal suspension is the natural sedimentation on a λ/10 polished substrate. Afterwards, the liquid is removed and the residue dried. After sedimentation, Atomic Force Microscopy (AFM) was used in order to check the surface structure of the samples. From AFM images (see figure) the free surface is observed to be a (111) face of an fcc crystal, size being also cross-checked. Fast Fourier Transforms of the images reveal that surface presents a perfect short range order (~20 μ). At long range, domains are observed with slightly different orientations due to defects and dislocations.



Bragg reflection is the optical test for bulk order and crystallinity. Bragg diffraction from the solid 3D arrangement of SiO_2 microspheres has been measured for samples with different lattice parameter (from 0.3 μ to 0.65 μ). Both first and second order Bragg peaks were observed. This has been used to determine the spacing of the particle planes. FWHM of the Bragg diffraction peaks are discussed in terms of both long range order and photonic pseudo-gap appearance. Different chemical methods to grow dielectric and semiconductor microparticles in the voids of the structure are proposed. Thus, threshold dielectric constant contrast in the composite could be achieved for gap appearance.

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Photonic band structures of two–dimensional compound systems: The face centered graphite lattices

Y.Chen

Laboratoire de Microstructures et de Microélectronique (L2M), CNRS, B.P. 107, 196 Avenue Henri Ravera, 92225 Bagneux, France

We describe the calculation of photonic band structures of two–dimensional compound systems made of more than one dielectric array. In particular, we study a face centered graphite (fcg) structure obtained by an arrangement of two sets of cylindrical rods, one located in six corners of regular hexagons and another in the center of the hexagons. Changing the diameter of the centered rods, different patterns can be produced including both simple triangle and two–dimensional graphite structures. We evaluate their relationships in terms of the existence of absolute photonic band gaps common to E and H polarized waves. We also propose a new technique of x–ray lithography for realizing the above describe lattices.

Investigation of photonic band gaps in a two–dimensional graphite structure made of GaAs

Y.Chen, G.Faini, J.Etrillard*, and H.Launois

Laboratoire de Microstructures et de Microélectronique (L2M), CNRS, B.P. 107, 196 Avenue Henri Ravera, 92225 Bagneux, France

**France Telelcom, CNET, Labortatoire de Bagneux, B.P.107, 196, avenue Henri Ravera, 92225 Bagneux, France*

We present an experimental investigation of photonic band gaps in a two–dimensional graphite structure made of GaAs. This structure is formed by an arrangement of parallel cylindrical rods of GaAs in six corners of regular hexagons. Because of the symmetry of the graphite structure, band gaps common to E and H polarized waves appear for relative *small filling parameters* [1]. By using standard electron beam lithography and reactive ion beam etching techniques, we obtained GaAs rods with a *high aspect ratio*. Typically, for quarter micron diameter rods and half micron nearest spacing, an etching depth of more than one micron was obtained. We present our initial results and discuss the outlook of this new photonic structure.

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Optical study of magnetically induced coupling of a quantum well and a semimagnetic semiconductor microcavity.

F. Kany, H. Ulmer-Tuffigo, R. André*, J. Bleuse, G. Feuillet, J.L. Pautrat

CEA, Département de Recherche Fondamentale sur la Matière Condensée/ SP2M/ PSC, 17 rue des Martyrs, 38054 Grenoble CEDEX 9, France

** Laboratoire de Spectrométrie Physique, Université Joseph Fourier, B.P. 87, 38402 Saint Martin d'Hères CEDEX*

Photon quantization in semiconductor microcavities, together with electron confinement in low-dimensional structures, allows a complete control of the radiative properties: if an active medium, consisting of 2D-confined electrons and holes, is put in an optical cavity where a single photon mode matches the energy of the active medium emission, then radiative recombination is allowed only in that precise photon mode, leading to extremely well-defined spectral characteristics of the resulting emission. It is possible to grow by Molecular Beam Epitaxy monolithic semiconductor microcavities consisting of a one wavelength thick Fabry-Perot cavity (embedding low-dimensional electronic heterostructures) sandwiched between two distributed Bragg reflectors.

The use of a semimagnetic semiconductor as the material constituting the microcavity gives an additional degree of freedom for coupling the photon mode with an exciton mode that is inserted in the cavity via a 2D electronic heterostructure. Applying a magnetic field in a semimagnetic semiconductor like CdMnTe produces a change of Δn in the optical index due to the Faraday effect: Δn is related to the field and the photon energy by the Verdet constant V, $\Delta n = 2\hbar c V B / E_{ph}$. The optical thickness $\lambda_0(1+\Delta n/n)$ of the cavity, and consequently the energy of the cavity mode, is therefore a tunable function of the magnetic field.

Our samples are based on microcavities made of a $Cd_{0.9}Mn_{0.1}Te$ layer embedded between $Cd_{0.3}Mg_{0.7}Te$/ $Cd_{0.9}Mn_{0.1}Te$ Bragg reflectors; some samples do not have the second Bragg mirror, in order to allow us to get the characteristics of the 'naked' quantum well inserted in the cavity (i.e. without having the effect of the complete cavity). By applying a magnetic field of 8T, we can split the cavity mode into two modes, observable in $\sigma+$ and $\sigma-$ polarizations, separated by 100Å. We present the results obtained for samples containing CdTe quantum wells; these wells are designed in order to obtain a resonance between the ground state heavy hole exciton and the cavity mode, and also a resonance between the ground state light hole exciton and the cavity mode. In both cases, the resonance between the exciton and the cavity mode can be achieved by tuning the magnetic field and is characterized by a large increase of luminescence efficiency demonstrating the effect of the cavity; we are attempting to increase the cavity finesse and to decrease the exciton linewidth in order to measure the Rabi splittings in our samples.

TIME-RESOLVED PHOTOLUMINESCENCE MEASUREMENTS ON STRONG COUPLING SEMICONDUCTOR MICROCAVITIES

B.Roycroft, J.P.Doran, J.O'Gorman, J.Hegarty, R.P.Stanley*, R.Houdre*, U.Oesterle*, and M.Ilegems*.

Physics Dept., Trinity College, College Green, Dublin 2, Ireland.

**Insitut de Micro- et Optoelectronique, EPFL, CH-1015, Lausanne, Switzerland.*

Recently there has been a great deal of interest in the physical properties of semiconductor microcavity structures and the many possible device advantages such structures possess. Control of the spectral and spatial emission characteristics in microcavities is relatively easy but control of the spontaneous emission rate is more difficult. In the standard weak coupling microcavities only small modifications of the spontaneous emission rate is possible but in the strong coupling regime more dramatic modification of the emission lifetimes have been anticipated. We measure cavity-polariton emission lifetimes in two strong coupling microcavity samples: one containing a single InGaAs quantum well and the other containing six quantum wells.

Because the cavity-polariton states are a mixture of exciton and photon states a simple mixed oscillator picture suggests that the emission lifetime of this state will be an average of the exciton lifetime and the photon lifetime of the cavity (≈ 1 ps). Changing the relative exciton and photon content of the cavity-polariton, by introducing detuning between the exciton and photon resonances, would, in this picture, bring about a change of the lifetime. This detuning is achieved by using a wedged cavity. We carry out such measurements under non-resonant optical pumping and find that only a minor modification of the emission lifetime occurs near zero detuning. Our results indicate that the observed emission lifetime is determined by relaxation dynamics of the excited population.

SIZE QUANTIZATION OF ACOUSTIC PHONONS IN MICROCRYSTALS EMBEDDED IN A GLASS MATRIX

N.Ovsyuk, and V.Novikov
Institute of Mineralogy and Petrology, Novosibirsk, 630090, Russia, e-mail: ovsyuk@uiggm.nsc.ru

We consider the influence of the matrix on the spheroidal and torsional vibrational modes of microcrystals, which brought about a new interpretation of the low - frequency Raman spectra. We have studied heterophase system, consisting of Ge microcrystals embedded in GeO_2 glass matrix [1]. To gain a better understanding of the influence of the crystal - matrix boundary we have also analyzed some other chemical compositions of microcrystals and matrices with different relations between elastic constants and densities such as CdS in GeO_2 matrix and Ag in SiO_2 matrix which were obtained in [2,3]. In [4] it was shown that due to selection rules for Raman scattering on spherical particles, only spheroidal modes with even angular momentum quantum numbers l can be seen in the Raman spectrum. However, in practice the form of the microcrystals in a glass matrix may have deviations from a perfect spherical one. In this case, the selection rules can be relaxed and not only spheroidal modes with even l, but torsional vibrational modes with odd l can be seen in the Raman spectra. The transverse surface mode with the angular momentum $l = 1$ is absent for microcrystals with a free surface. This is natural, because this mode corresponds to the rotation of the microcrystal as a whole. If a microcrystal is embedded in a matrix, then there appears a new solution for the surface mode with angular momentum $l = 1$.This mode arises because of the restoring force which limits rotation of the microcrystal. Most likely, just these vibrations with $l = 1$ take part in the low-frequency Raman scattering described in [2,3].

From all our experiments it is clear that the depolarized Raman scattering is governed by the surface torsional modes with $l = 1$ which appear, when the crystals are embedded in a matrix. Furthermore, contrary to refs .[2,3], from the calculations follows that the influence of the matrix on the frequencies of the acoustic phonons, confined in the microcrystals, is significant even if Lame's constants λ, μ and the mass densities of the microcrystal and the matrix are quite different from each other.

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II-VI WEAK COUPLING MICROCAVITY STRUCTURES

T.Aherne, J.P.Doran, J.Hegarty, A.Salokatve*, P.Uusimaa*, K.Rakennus*, M.Pessa*

Physics Department, Trinity College, College Green, Dublin 2, Ireland.

**Tampere University of Technology, Physics Dept., FIN-33101 Tampere, Finland.*

Semiconductor microcavity effects in III-V materials are currently undergoing extensive investigations. In addition to the interesting physical phenomena that these structures exhibit they also possess distinct device advantages *e.g.* very high external quantum efficiencies. There is an obvious desire to replicate these effects in II-VI structures which operate at blue wavelengths.

Obtaining II-VI Bragg mirrors for blue wavelengths has been, however, a serious difficulty because of the relatively small refractive index differences that occur between suitable layer materials and difficulties with the stability of the growth rate of II-VI's. We have demonstrated reliable growth of ZnSSe/ZnMgSSe Bragg mirrors, with reflectivities of 90%, by incorporating *in situ* optical reflectometry during growth.

A 1λ ZnSSe microcavity was grown containing three 6 nm CdZnSe quantum wells situated at the electric field antinode of the cavity. The back mirror consists of a 24 period ZnSSe/ZnMgSSe Bragg mirror and the front mirror is formed by the semiconductor-air interface. The cavity is wedge shaped, which brings about a shift of the of the cavity resonance as one moves across the sample. At some point on the sample the cavity and exciton resonances coincide and at this point we observe a maximum integrated emission intensity and also the minimum reflectivity of the cavity resonance also reaches a minimum value at this point. These results demonstrate the achievement of a weak coupling II-VI microcavity.

Strong coupling regime in pillar semiconductor microcavities.

J. Bloch, J.M. Gérard[(a)], D. Barrier[(a)], J.Y. Marzin[(a)], R. Planel,

V. Thierry–Mieg and E. Costard[(b)]

L2M/CNRS, 196 avenue Henri Ravera, 92225 Bagneux, France

(a) France Télécom/CNET/PAB (b) Thomson–CSF/LCR

We report here on the optical study of pillar semiconductor microcavities containing quantum wells (QW). For the first time, we observe the strong coupling between the excitons and discrete three dimensionally (3D) confined cavity modes.

Our samples have been grown by Molecular Beam Epitaxy (MBE). They contain two GaAs/AlAs quarter–wave Bragg mirrors surrounding a λ GaAs cavity. In the center of the cavity we inserted two 12 nm $In_{0.14}Ga_{0.86}As$ QW in sample A and a single array of InAs Quantum Boxes (QB) in sample B. More than 200 lines of pillar microcavities with a radius ranging from 10 to 0.3 μm have been processed on both samples using electron–beam lithography and reactive ion etching.

We have used Photoluminescence (PL) at 5K to probe the 3D cavity modes of both samples. Since a low density of states is associated to the QB array, this broad band light emitter allows to measure very precisely on sample B the energy and the linewidth of the cavity modes in the weak coupling regime. We compare PL spectra measured at 5K on both samples. In sample A the high order 3D modes are much more intense than in sample B, compared to the fundamental mode. Moreover the mode that is the closest under the exciton line is slightly pushed away from the exciton. All these features are indicative of the strong coupling between the exciton and the 3D cavity modes.

By taking advantage of the lateral inhomogeneity of the MBE growth, it is possible to tune the cavity resonance of sample A with respect to the QW heavy hole exciton by changing the pillar line under examination. When moving toward the resonance we observe an anticrossing behavior between the exciton and the cavity mode lines which is a signature of the strong coupling between the exciton and the cavity modes. At resonance either with the first or the second mode, we observe a 2.4 meV Rabi splitting.

STUDY OF PHOTONIC BAND STRUCTURE OF 3D ORDERED SILICA MATRICES

V.N.Astratov, V.N.Bogomolov, A.A.Kaplyanskii, O.Z.Karimov, A.V.Prokofiev and Yu.A.Vlasov

A.F.Ioffe PTI, St.-Petersburg, Russia, Fax:(812)2471017, E-mail:astra@splab.ioffe.rssi.ru

Recently synthesized porous silica matrices (so called synthetic opals) possess a highly ordered regular 3-D structure (closely packed cubic lattice of equal diameter silica spheres) with the period about 0.2-0.4 micron that allows to probe their photonic band structure by visible light [1].

In transmission spectra taken at normal incidence two well pronounced drops (attenuation 1/e on the length about 100 opal lattice constants) were observed within the region of transparency of the silica and were ascribed to first and second order PBG's for a given direction of light propagation that is confirmed by observation of corresponding maxima in reflectance spectra. In the transmission spectra measured at different orientations of incident beam relative to the sample facets the spectral positions of the drops were found to be shifted by an amount exceeding their spectral widths. This shift was explained by "semimetallic" photonic band structure in consistence with the theory for fcc lattice with spherical "atoms" to which the opal structure belongs.

Basing on the theoretical estimations [2] it was shown that the filling of pores of opals by a semiconductor can provide essentially deeper depletion of photon density-of-states within PBG in comparison with unfilled opal matrices. In attempt to make such a system the vapour phase synthesis of CdS microcrystals in the pores of opals was applied. The results of optical studies (PL, Raman scattering) demonstrate good crystallinity of CdS microcrystalls embedded in opal matrix and exhibit well-pronounced quantum confinement effects in fundamental edge absorption spectra.

Due to possibility to vary most of important parameters (modulation of refractive index, packing volume fraction, period et al) synthetic opals can be considered as a suitable model system for studying of photonic band gap (PBG) effects in visible region.

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Strain effect on the excitation threshold of HgCdZnTe heterostructure lasers in the 3—5 μm waveband

Joël Bonnet-Gamard, Joël Bleuse, Guido Mula and Noël Magnea

CEA, Département de Recherche Fondamentale sur la Matière Condensée/ SP2M/ PSC, 17 rue des Martyrs, 38054 Grenoble CEDEX 9, France

The competition between radiative and non-radiative recombinations in semiconductor materials is one of the main limiting factors in the making of low excitation infrared threshold lasers. The solution found for the telecom InGaAs/ InP lasers, which emit at 1.55 μm, consists in adding uniaxial compressive stress to the emitting layers. This results in a lowering of the state density around the valence band maximum, and consequently of the carrier density needed to reach the population inversion. The Auger processes become then less a limitation in the competition with the radiative recombination, their probabilities being proportional to the cube of the carrier density.

Longer wavelengths lasers, which are needed to, *e.g.*, probe gas pollutants in the atmosphere (CO, CH_4, HCl, N_20, O_3... present strong absorption lines in the 3—5 μm atmospheric transparency window) should benefit from this principle.

Following this path, we study HgCdZnTe quaternary-based waveguide heterostructure lasers, grown by molecular beam epitaxy on ⟨0 0 1⟩-oriented $Cd_{0.88}Zn_{0.12}Te$ substrates. The emissive layers are HgCdTe quantum wells, compressively strained because of a lattice parameter mismatch of about 0.5%. The waveguide is made of graded composition layers. The first sample emits around 3 μm. We compare it to a HgCdTe ternary-based unstrained sample, grown on a $Cd_{0.96}Zn_{0.04}Te$ substrate. The characteristic temperature of the excitation threshold[1] raises from 31 K on the unstrained sample to 44 K on the strained one. The maximum lasing temperature is similar for the two samples : 150 K and 165 K respectively. The 4 μm-emitting sample presents a 280 W cm^{-2} threshold at 30 K and 27 kW cm^{-2} at the maximum lasing temperature : 160 K. This corresponds to a 28 K characteristic temperature, a 30% improvement over the values of unstrained samples. All these samples still exhibit a high internal loss (estimated to 30 cm^{-1}), that could be due to the presence of pyramids on the ⟨0 0 1⟩ orientation. The present work shifts on strained samples grown on ⟨1 1 2⟩-oriented substrates, which are free from these defects.

[1] The excitation threshold temperature dependence is fitted to $S_0 \exp(T/T_0)$ where T_0 is the characteristic temperature.

TIME DEPENDENT EXCITON SPECTROSCOPY IN $Zn_{1-X}Cd_XSe$/ZnSe MULTIPLE QUANTUM WELL LASERS

D. Greco, L. Calcagnile, and R. Cingolani
Istituto Nazionale di Fisica della Materia-Dipartimento di Scienza dei Materiali, Università di Lecce, Via per Arnesano, I-73100 Lecce, Italy

M. Lomascolo and M. Di Dio
Centro Nazionale Ricerca e Sviluppo Materiali (PASTIS-CNRSM), SS 7 Appia Km 713, I-72100 Brindisi, Italy

L. Vanzetti, L. Sorba,* and A. Franciosi*
Laboratorio Nazionale Tecnologie Avanzate Superfici e Catalisi dell' Istituto Nazionale per la Fisica della Materia, Area di Ricerca, Padriciano 99, I-34012 Trieste, Italy

The competition between localized and free exciton recombination in ZnCdSe/ZnSe multiple quantum well (QW) structures has been investigated by means of temperature dependent time resolved luminescence (TRPL) experiments, from well below up to about the threshold for lasing. The temperature (T) dependence of the exciton luminescence decay time provides relevant information on the polariton confinement in the quantum well. The exciton dynamics is found to be governed by the polariton effect (contributing with a linear T-dependence of the decay time τ) and by the thermal escape of carriers from the QW at relatively high temperatures (implying a decrease of τ with the temperature). In the shallow quantum wells the decay time increases almost linearly with the temperature, then it saturates and starts to decrease around 100 K. At this temperature the less confined particle, presumably the heavy-hole, is thermally activated above the barrier and the exciton itself becomes unstable. In the deep quantum wells the saturation is observed, but the depth of the QW is large enough to prevent thermal escape of the carriers up to room temperature.

The excitation intensity dependence of the TRPL at low temperature (T=10K) elucidates the contribution of the exciton localization to the radiative recombination mechanism. At low injection density (10^9 cm^{-2}), a clear localized exciton behaviour has been observed. Increasing the carrier density up to the lasing threshold, shallow QW samples exhibit a shortening of the luminescence (PL) raise and decay times, and a blue shift of the time-integrated PL peak. This demonstrates a saturation of the localization centers in samples where compositional and strain fluctuations are not expected to play a dominant role. Deep quantum wells (high cadmium content) do not exhibit a significant change of τ nor a blue shift even under strong pump fluences, evidencing that the localized exciton character of the luminescence dominates up to high injection densities. Close to lasing threshold the shallowest heterostructure exhibits a typical free-carrier recombination and a band filling effect in the form of a "plateau" region in the transient PL trace. On the contrary, Cd-rich samples evidence a localized exciton emission, due to the strong compositional fluctuations, even above lasing threshold.

A rate equation model describes the temporal evolution of the luminescence, including the thermodynamical phase diagram of the localized exciton, free-exciton and free-carrier populations, and a density dependent factor accounting for the saturation of the localization centers. Our results elucidate the role of localization in the lasing process, and clarify the competition between the localized exciton and free-carrier recombination through the quantitative determination of the density of localization centers existing in the crystal (connected to compositional disorder).

Spatial Expansion of Exciton Magnetic Polarons in $Zn_{1-x}Mn_xSe/ZnSe$ Multiple Quantum Wells

G. A. Balchin, C. D. Poweleit, L. M. Smith
Department of Physics, University of Cincinnati, Cincinnati, OH 45221-0011
B. T. Jonker
Naval Research Laboratory, Washington, D.C.

Using spatially- and temporally- resolved photoluminescence we measure the spin transport of exciton magnetic polarons in symmetric, 10-nm $Zn_{1-x}Mn_xSe/ZnSe$ multiple quantum wells. The exciton magnetic polarons in these quantum wells are spatially indirect, with the hole confined to the magnetic $Zn_{1-x}Mn_xSe$ and the electron confined to the non-magnetic ZnSe. As a result, the lifetime of the EMP is over 10 ns, three orders-of-magnitude longer than the lifetime of the free exciton (100 ps). Polarized time-resolved magneto-photoluminescence measurements at small magnetic fields are used to estimate the number of spins involved in formation of this type-II exciton.

At low temperatures and zero field, the Mn-spins within the Bohr radius of the exciton magnetic polaron are nearly completely saturated. Transport of the EMP therefore involves movement of the Mn-polarization as well as the physical movement of the electrons and holes. To measure this spin-transport, we have constructed a confocal microscope where the microscope objective is within a liquid-helium cooled cryostat. The spatial- and temporal-resolution of this system approach 1μm and 50 ps, respectively. We find that at low temperatures (< 9 K) the transport of EMP is strongly temperature dependent, with the diffusivities approaching 25 cm^2/s at 2 K and going to zero by 9 K. In contrast, we are unable to observe any diffusion of the bare excitons at any temperature. Indeed, the diffusion constant of the EMP at 2 K is equivalent to an effective mobility greater than 100,000 cm^2/Vs. These unphysically large mobilities and the strong temperature dependence suggests that the EMP must be *driven* away from the excitation point. Possible candidates responsible for the origin of this repulsive force will be discussed.

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INTERFERENCE EFFECTS IN ELECTRICAL RESISTIVITY AND SPIN-VALVE MAGNETORESISTANCE IN MAGNETIC LAYERED STRUCTURES

J. Barnaś* and Y. Bruynseraede, Laboratorium voor Vaste-Stoffysika en Magnetisme, K.U. Leuven, Belgium

Electronic transport in artificially layered magnetic and nonmagnetic metallic structures has been analysed theoretically, with particular attention paid to the quantum effects in electrical resistance and spin-valve magnetoresistance in structures consisting of two ferromagnetic films separated by a nonmagnetic layer. The spin-valve magnetoresistance is then due to rotation of the film magnetizations from antiparallel to parallel alignment. In the parabolic approximation for the electronic bands the resistivity and magnetoresitance are shown to oscillate with two different periodicities with increasing thickness of the nonmagnetic spacer layer. The short oscillation period is determined by the appropriate Fermi wavelength and is equal to the oscillation period occuring in the exchange coupling between the magnetic films across the spacer. The second oscillation period is significantly longer and is determined by the height of the potential steps at the interfaces between the magnetic and nonmagnetic films. The physical mechanism leading to the long-period oscillations in the resistivity and magnetoresistance consists in an interplay of the partial electron confinement in a quantum well created by the potential steps and the electron scattering by rough interfaces. If the interfaces are perfectly flat, then the amplitude of the long-period oscillations vanishes, whereas the short-period oscillations survive. The oscillations in magnetoresistance and in the interlayer coupling parameter are then correlated. Maxima of the spin-valve magnetoresistance correspond to the maxima of the ferromagnetic-type interlayer coupling. Similar oscillations also occur in the dependence of the resistivity and magnetoresistance on the thickness of magnetic films.

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* Permanent address: Institute of Physics, A.M. University, Poznań, Poland.

Raman Scattering from a Magnetically Modulated 2DEG Subject to a Normal Magnetic Field

V. Fessatidis[a], H. L. Cui[b], and P. Vasilopoulos[c]

[a]*Department of Physics, Fordham University, New York 10458 U.S.A.*

[b]*Department of Physics and Engineering Physics, Stevens Institute of Technology Hoboken, New Jersey 07030 U.S.A.*

[c]*Department of Physics, Concordia University Montreal, Quebec, Canada H3G 1M8*

E-Mail: hcui@phdec1.stevens-tech.edu Fax: (201)216-5638

An analysis of electronic Raman light scattering from a two-dimensional electron gas (2DEG) subject to a *weak periodic* magnetic modulation of strength B_0 and to a perpendicular uniform magnetic field B of arbitrary strnegth is presented. Raman spectra are calculated for: i) electron inter-Landau-level transitions, which result in a Raman shift $\sim 2\omega_c$, bearing corrections due to the finite width of the Landau levels resulting from the modulation; ii) inter-Landau-level collective electron excitations at both the hybridized magnetoplasmon frequency and at a *new* low-frequency, an intra-Landau-level plasmon mode induced by the modulation. The dependence of the Raman cross sections on the strength of B and B_0 is assessed. Both 1D or 2D spatial modulations of the magnetic field (achievable, *e.g.*, by patterned deposition[1] of magnetic materials on top of the AlGaAs layer of the quantum well containing the 2DEG, are considered and their effects on the Raman spectrum are investigated and compared with those of the electric modulation. The effects of a weak B_0 on the Raman spectrum are in one to one correspondence with those of the electric modulation[2] but the magnetic modulation leads to much stronger Raman signals. The combined effect of 1D electric and magnetic modulations is also considered. It is shown that electronic Raman scattering provides an independent, spectroscopic probe of the physics of these modulated structures. In conjunction with this, possible experimental forms of the many-faceted Raman spectra are indicated and analyzed.

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Gate voltage induced realization of different rational fractions of h/e^2 at fixed values of current and magnetic field

M. Blöcker°, G. Nachtwei*, F.J. Ahlers° and L. Bliek°

° Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig

* Max-Planck-Institut für Festkörperforschung, Heisenbergstr. 1, D-70569 Stuttgart

We present magnetotransport measurements on patterned GaAs/$Al_xGa_{1-x}As$-heterostructures consisting of two parallel Hall bars connected via wide regions of 2DEG. This leads to a 'windowed' structure with a surface gate across each of the Hall bars. Two types of samples with potential probes below or next to the gates are investigated.

By setting the gate voltages and the magnetic field to appropriate values, different integer filling factors in all sample regions can be realized. With this we are able to generate Hall resistances with values of different rational fractions of h/e^2 while current and magnetic field are kept constant.

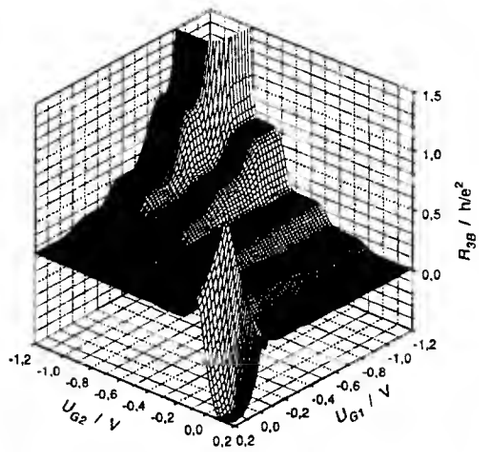


Figure 1: Hall resistance R_{3B} showing plateau values of different rational fractions of h/e^2 at ν_0=4.

Whereas measurements on samples with Schottky gates are usually considered being showpieces for the validity of Büttikers edge channel picture of the IQHE, we show that our measurements can be interpreted in the edge channel picture as well as by solely applying Kirchhoff's laws. This is in agreement with results by Thouless [1] that the potential distribution on the sample edge in the IQHE is not affected by the transfer of portions of the current into the bulk.

While the measurements with integer filling factors below both gates yield identical results for samples with potential probes below the gates as for those with potential probes next to the gates, measurements with non-integer filling factors below one gate lead to different results. A model for this finding is presented.

[1] D. J. Thouless, *Phys. Rev. Lett.* **71**(12) 1993, pp. 1879

Circular Inhomogeneous Magnetic Field Profiles in Electron Waveguide Junctions

Xin-Qi Li and F. M. Peeters
Department of Physics, University of Antwerp (UIA), B-2610 Antwerpen, Belgium

Based upon a semi-classical approach we perform a numerical simulation for the scattering of electrons on an inhomogeneous magnetic field profile which is located in the cross of a Hall bar system. In the semi-classical formalism, the current in each probe can be obtained by the Büttiker formula, and the Hall resistance can be further expressed in terms of the transmission probabilities. To obtain the probabilities, in our numerical simulation, we inject a large number of electrons, say $N_e \geq 4 \times 10^4$, towards the junction through one lead, and follow their trajectories to determine the probabilities for transmission in the different leads.

Some representative results are shown in the figure for the case the magnetic profile is $B(r) = 0$ for $|r| < d$ with d the radius of the dot, otherwise $B(r) = B$. In our result, the magnetic field is in unit of $B_0 = mv_F/2eW$, and the resistance in $R_0 = (h/2e^2)\pi/2k_FW$, where W is the half width of the lead, $k_F = \sqrt{2m\epsilon_F/\hbar^2}$ and $v_F = \hbar k_F/m$ are respectively the Fermi wave vector and velocity, m being the mass of the electron. We notice that there exists a critical magnetic field B_c, such that for $B > B_c$ the Hall resistance in the presence of the disk profile coincides with that in the absence of the disk (solid line in Fig. (a)). For $B < B_c$ the Hall resistance is sensitive to the size of the dot. For $B > B_c$ the electron motion is determined by the edge states which are located along the edge of the device, and they do not sample the cross region. For $B << B_c$ the electrons sample the magnetic field profile present in the cross region. It turns out that the Hall resistance is well described by a renormalized field which is equal to the average field in the cross (see Fig. (b)).

This system can be used as a new experimental tool which measures the local magnetic flux. We have performed a detailed analysis and determined the relation between the value of the Hall resistance and the magnetic field profile in the cross of the Hall bar. Therefore, we extended our analysis to the case of inhomogeneous magnetic field profiles produced by ferromagnetic disks and superconducting disks on top of such a Hall bar.

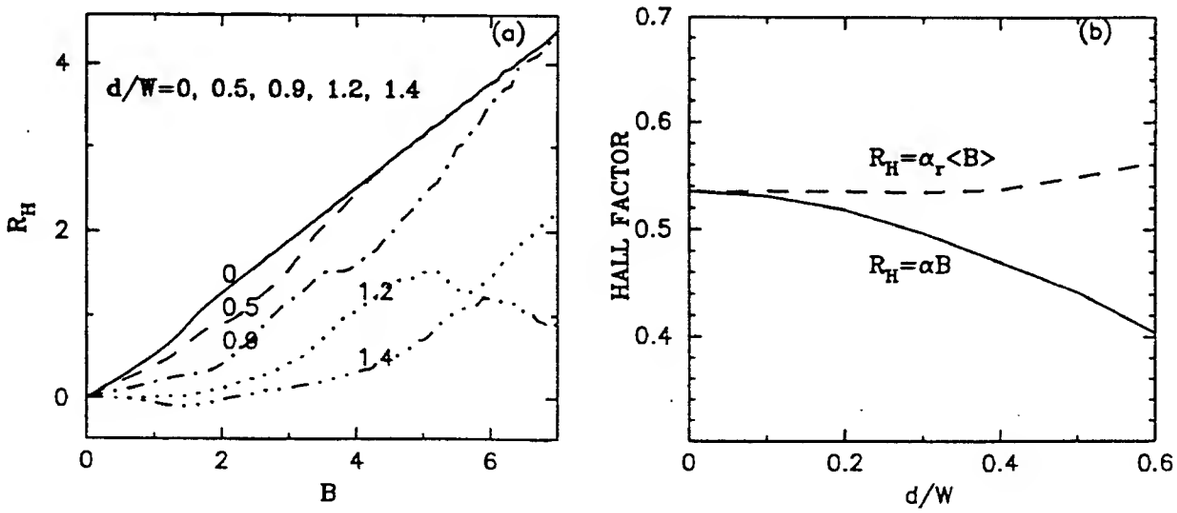


Figure: (a) Hall resistance in the presence of a superconducting dot in the cross junction, where the results for different sizes of the disk are shown. (b) Hall factor in the low magnetic field regime.

Inductive Probing of the Integer Quantum Hall Effect

E. Yahel [1], D. Orgad[2], A. Palevski[1], H. Shtrikman[2]

[1] *School of Physics, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel*

[2] *Department of Condensed Matter, The Weizmann Institute of Science, Rehovot 76100, Israel*

Abstract

We investigated the Integer Quantum Hall Effect (IQHE) on samples having a Corbino and Hall bar geometries, using a new inductive method. We found that the redistribution of currents as one enters into the IQHE regime is mainly determined by classical electrostatics. The latter is strongly influenced by the gates, Ohmic contacts, etc. From the measurements we conclude that substantial amount of the Hall current flows in the interior of the 2DEG system (bulk states).

However, for Hall bar geometries we were able to obtain the small contribution of the edge currents to the measured signal. we find that the contribution of the edge currents varies continuously, being maximal at the beginning of the plateau and minimal at its end.

Quasiparticle lifetime τ_{ee} of electron-electron interactions for 2D electron gases with magnetic field

Sheng Xu[1], X.C. Xie[1], T. Kawamura[2] and Ben Yu-Kuang Hu[3]

[1] *Department of Physics, Oklahoma State University, Stillwater OK 74078, USA.*
[2] *Department of Physics, State Univ. of New York, Stony Brook, NY 11794, USA.*
[3] *Mikroelektronik Centret, Danmarks Tekniske Univ., DK-2800 Lyngby, Denmark.*

The quasiparticle lifetime τ is a central quantity in the theory of interacting electron systems. Since it is related to the electron energy dissipation rate, it is an important factor in the operation of electronic devices. There have been extensive theoretical and experimental studies of the Coulomb scattering of electrons in a two-dimensional electron system in the absence of magnetic field. We extend these theoretical studies by including a finite magnetic field, and study in particular the weak magnetic field limit. By using the random-phase approximation and the magnetoplasmon-pole approximation, we systematically study the magnetic field, temperature and disorder dependences of the quasiparticle lifetime τ_{ee} due to electron-electron interactions for a two-dimensional electron gas. The τ_{ee} shows an oscillatory behavior as a function of magnetic field B, reflecting the underlying Landau level density of states. The average $\tau_{ee}(B)$ *increases* with the increasing B-field; *i.e.*, it has exactly the opposite dependence to the impurity scattering time. We also find that for all B-fields studied, τ_{ee} monotonically decreases with temperature, as in the zero field case. The predicted behavior of τ_{ee} with respect to B and T should be observable in double-well tunneling experiments [1].

[1] S. Q. Murphy, J. P. Eisenstein and K. W. West, Phys. Rev. B **52**, 14825 (1995).

Strong Dependence of the Multichannel Ballistic Transport on the Geometrical Symmetry

Mincheol Shin, Kyoung Wan Park, Seongjae Lee, and El-Hang Lee

Electronics and Telecommunications Research Institute, Yusong POB 106, Taejon, Rep. of Korea

In the study of the ballistic electron transport in an Aharonov-Bohm-type ring structure, the extension from the single-channel problem to the more realistic *multichannel* one becomes difficult because of the *interchannel* scattering effect which is an essential ingredient of the multichannel transport. We have found that in designing the multichannel S-matrix one must carefully consider the symmetry relationships of the constituting transmission amplitudes and that *the Aharonov-Bohm-type conductance oscillations are strongly dependent on the symmetry of the S-matrix when the interchannel scattering is taken into account.* For the planar ring of Fig. 1-(a), the mirror-plane symmetry demands that $s_{21,mn} = (-1)^{n+1} s_{31,mn}$ and $s_{23,mn} = s_{32,mn}$, where $s_{ji,nm}$ is the transmission amplitude from mode m of region i to mode n of region j, while the vertical ring of Fig. 1-(b) has the relationships of $s_{21,mn} = (-1)^{m+n} s_{31,mn}$ and $s_{23,mn} = (-1)^{m+n} s_{32,mn}$. These different phase factors dictated by the different geometrical symmetries lead to the dramatic effects that when the interchannel scattering is maximal, the amplitudes of the h/e oscillations for the planar ring *vanishes completely* as the temperature is raised, while that for the vertical ring develops into the $h/2e$ oscillations which do *not* vanish. We have obtained the interesting results by devising a convenient scheme for controlling the interchannel scattering strength by the appropriate unitary transformation of the S-matrix.

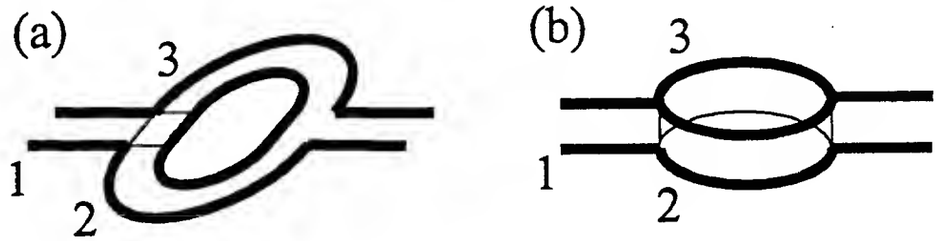


FIG. 1. The ring structures with different symmetry: (a) planar ring, (b) vertical ring.

FORCING OF CHAOS IN SEMICONDUCTOR SUPERLATTICES

L. L. Bonilla and O. M. Bulashenko

Universidad Carlos III de Madrid, Butarque 15, E-28911 Leganés, Spain

Dynamic properties of high-field transport in weakly-coupled narrow-miniband GaAs/AlAs superlattices (SL) under $ac + dc$ biases have been numerically studied within a self-consistent discrete model [1]. Experiments have established that a charge accumulation layer (domain wall) connecting two electric field domains is formed in a SL subjected to pure *dc* bias [2]. Depending on the doping concentration, the domain wall can be stable (for higher doping) or unstable (for lower doping). In the latter case self-sustained periodic current oscillations are observed.

In this contribution we study the dynamic properties of electron transport in SL by superimposing an additional small *ac* signal to the *dc* voltage bias. We consider two cases characterized by the behavior under *dc* voltage bias:

(i) The regime of stationary charge accumulation layer and stationary electric field domains. Under *dc* voltage bias, the SL exhibits multistability and hysteresis. The additional periodic forcing results in a quite complicated bifurcation picture including period-doubling cascades, quasiperiodicity and chaos.

(ii) The regime of self-sustained oscillations, caused by the periodic motion of the charge accumulation layer over the SL. It is shown that an additional external microwave signal gives rise to quite different domain-wall dynamics: mode-locking, quasiperiodicity or chaos depending on the parameters of the forcing [3]. On the driving frequency – driving amplitude parameter plane, there are regions of entrainment and quasiperiodicity forming Arnol'd tongues. Chaos appears at the boundaries of the tongues and in the regions where they overlap. The Lyapunov exponents are calculated to identify chaotic solutions and to characterize their fractal dimension.

It should be noted that experimental results on nonlinear dynamics in periodically driven SL obtained very recently by the group of H.T.Grahn (Paul-Drude-Institute, Berlin) seem to bear out our predictions of chaos.

[1] L. L. Bonilla et al., Phys. Rev. B **50**, 8644 (1994).

[2] J. Kastrup et al., Phys. Rev. B **52**, 13761 (1995).

[3] O. M. Bulashenko and L. L. Bonilla, Phys. Rev. B **52**, 7849 (1995).

DX-Center and Pressure Effects on Electronic Structure of a δ-Doped Quantum Barrier

J.M. Shi,[*,#] *P.M. Koenraad,*[#] *A.F.W. van de Stadt,*[#]
F.M. Peeters,[*] *J.T. Devreese,*[*,#] *and J.H. Wolter*[#]

*Departement Natuurkunde, Universiteit Antwerpen (UIA), B-2610 Antwerpen
#Departement Natuurkunde, Technische Universiteit Eindhoven, NL-5600 Eindhoven

We investigate structures where a Si δ-doped layer is located at the center of a GaAs/Al_xGa_{1-x}As/GaAs quantum barrier. Such structures can provide three useful advantages as compared to normal δ-doped GaAs [1]: 1) the influence of the barrier differs for the different subbands. This makes it possible to control the energy gaps between the electron subbands; 2) the barrier "pushes" the electrons away from the impurities. Consequently the electron mobility of the system is expected to be enhanced; and 3) because the Si dopants reside in the Al_xGa_{1-x}As barrier and the energy position of the DX center relative to the conduction band depends on the Al fraction, it becomes possible to tune the difference between the DX and Fermi levels.

Therefore our "samples" can be prepared to contain a different fraction of their free electrons trapped on DX centers whereas other electronic parameters of the samples, like the shape of the wave functions, are hardly changed. Also the hydrostatic pressure needed to change the fraction of electrons trapped on DX centers can be modest and tuned to an accessible experimental range of pressures. Thus correlation effects affecting e.g. the free electron density and the electron mobility can be studied in detail.

By solving the coupled Schrödinger and Poisson equations of the system, the wave functions, energy levels, and electron density of the subbands were obtained as well as the one-dimensional effective confinement potential and the Fermi energy. In order to study the influence of the DX centers on the electronic properties of the system [2], three models are discussed at non-zero temperature and under hydrostatic pressure in the absence (DX^0_{nc}) and in the presence (d^+/DX^0 and d^+/DX^-) of spatial correlations in the charge distribution. We found that: 1) increasing the quantum-barrier height and applying hydrostatic pressure are helpful to experimentally observe the effects of the DX centers through a decrease of the total free-electron density; 2) the electron wave functions are more spread out with increasing barrier height, and the presence of DX centers changes the carrier density and the arrangement and/or the number of charged impurities; and 3) the impurities become ionized in such a way that they are spatially correlated. This is important in the calculation of the electron mobility which becomes enhanced.

[1] P.M. Koenraad *et al.*, Physica B **211**, 462 (1995).
[2] P. Sobkowicz *et al.*, Semicond. Sci. Technol. **7**, 1155 (1992).

Magnetic-field-induced Reduction of Singlet Binding Energies of Off-well-center Negative Donor Ions in GaAs/AlGaAs Multiple Quantum Wells

Z.X. Jiang[+], B.D. McCombe[+], Jia-Lin Zhu[+], and W. Schaff[*]---[+]*SUNY at Buffalo, Buffalo, NY 14260, USA;* [*]*School of Engineering, Cornell University, Ithaca, NY 14853, USA*

There has been substantial recent interest in negative donor ions (D^-) in semiconductor quantum wells (QWs). The energy states of D^- depend delicately on a balance between the electron-electron repulsion and the attractive interactions of the electrons with the positively charged impurity centers. For impurities at the QW centers, confinement greatly enhances the binding energy for both neutral donors (D^0) and D^- ions. However, very different magnetic field effects have been predicted for off-well-center D^- ions. When donors are located more than quarter of the well width away from the center, the singlet binding energy is predicted to increase, and then decrease with increasing magnetic field, finally become negative (dissociation). To test these calculations, we have carried out far-infrared Fourier transform magneto-transmission spectroscopy up to 15T at low temperatures on two multiple QW samples with nominally the same structure (200Å wells / 600Å barriers). Samples are δ-**doped** (Si) in the wells 3/4 of the way from the center to the edge of the wells at 2×10^{10} cm^{-2} (sample A), and δ-doped identically in the wells and δ-doped in the barrier-centers at 3×10^{10} cm^{-2} (sample B). Temperature- and magnetic-field-dependence studies have been used to identify the features in the spectra. As expected, the singlet and triplet binding energies for off-well-center D^- are smaller than their well-center counterparts. In striking contrast to the well-center D^-, the intensity of the off-well-center D^- singlet transition decreases with increasing magnetic field between 5.5T and 15T at all temperatures studied (2.5K-25K), while the D^0 1s-$2p^+$ transition increases in strength at the expense of the D^- singlet. These results reflect directly the importance of the repulsive electron-electron interaction in this unique system, which is "tuned" by the magnetic field. The shifted triplet transition has also been observed at 2.5K. Experimental results are in good agreement with the recent theoretical predictions.

[+] Supported in part by ONR

ACCUMULATION LAYER AND INTERFACE EFFECTS IN DOPED NONABRUPT $GaAs/Al_xGa_{1-x}As$ SINGLE QUANTUM WELLS

Alexander K. Freire, Eraldo C. Ferreira, Gil A. Farias, and Valder N. Freire*
Departamento de Física, Universidade Federal do Ceará, Caixa Postal 6030
Campus do Pici, 60455-760 Fortaleza, Ceará, Brazil
*Departamento de Física Teórica e Experimental, Campus Universitário
Universidade Federal do Rio Grande do Norte, Caixa Postal 1641
59072-970 Natal, Rio Grande do Norte, Brazil

Recently, it was shown that accumulation layer and interface effects on doped nonabrupt $GaAs/Al_xGa_{1-x}As$ heterojunctions can modify their energy levels [1]. By investigating interfaces of $GaAs/Al_xGa_{1-x}As$ multilayers highly doped with Be (10^{18} cm^{-3}), Salemink *et al* [2] have observed an interface region of two to three unit cells in the charge density contours, and a transition region of six to nine unit cells wide with tunneling spectroscopic measurements. A study of the energy levels in doped nonabrupt $GaAs/Al_xGa_{1-x}As$ single quantum wells is done in this work. By using the interface description of Freire *et al* [1], the energy levels of $GaAs/Al_{0.3}Ga_{0.7}As$ 100 Å wells are calculated. Interfaces varying from zero to four GaAs unit cells are take into account, as well as band bendings of 0-90 meV. It is obtained that the interface effects on the energy levels and wave functions are very important and sensitive to the level of doping. When interfaces of only two GaAs unit cells and a band bending of 40 meV is considered, the ground state (first excited state) energy level shifts toward high energies as much as 5 meV (19 meV).

[1] Presented at the Eight International Conference on Superlattices, Microstructures and Microdevices, held in Cincinnati, USA, 1995, and published by A. K. Freire, J. Ribeiro Filho, G. A. Farias, and V. N. Freire, Superlatt. Microstruct. **17**, 351 (1995).
[2] H. W. M. Salemink, O. Albrektsen, and P. Koenrad, Phys. Rev. B 45, 6946 (1992).

INTERFACE ROUGHNESS: A REASON FOR INACCESSIBILITY OF THE NEGATIVE RESISTANCE REGION IN RESONANT–TUNNELLING DEVICES

T. Figielski, T. Wosiński and A. Mąkosa
Institute of Physics, Polish Academy of Sciences
Al. Lotników 32, 02-668 Warszawa, Poland

Double-barrier resonant-tunnelling devices (DBRTDs) are thought to be prospective sources of microwave and millimetre-wave power as they can exhibit negative differential resistance (NDR) region in the current-voltage characteristics. However, real DBRTDs very seldom display smooth NDR region required for the controllable performance of such devices. Usually, the resonant maximum of the tunnel current versus bias voltage of DBRTD ends in either **single step** or **double step**. The latter feature appears as a broad shoulder beyond the principal resonance peak and commonly displays some irregular structure. The view has been generally taken that the shoulder is an artifact rather than intrinsic property of DBRTD and is due to self-oscillations arising in the NDR region of the device.

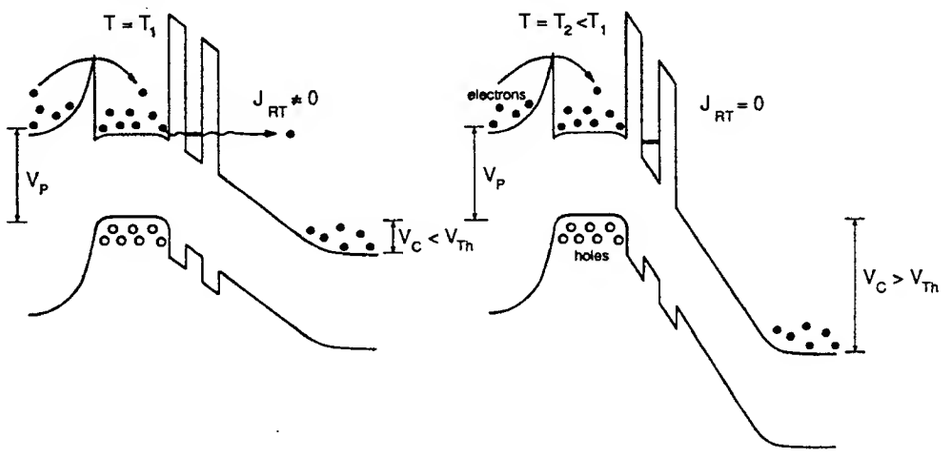
By studying GaAs/AlGaAs-based DBRTDs we have shown, with no room for a doubt, that even when the oscillations were completely suppressed the shoulder did remain. We have also demonstrated that the shoulder frequently consists of several broad peaks and that its appearance is connected with a peculiarity of the electron lateral motion in real quantum well having rough boundaries.

The boundary roughness may be thought about as different-size islands of ± one-monolayer height adjacent to the otherwise flat interface. The island-bordering steps are effective scatterers for electrons. In general, there are several space periods, L_i, in the lateral distribution of these scatterers that are defined by the Fourier transform of the roughness profile. If an electron moving in the well has at least such kinetic energy that its in-plane wavevector $k_{||}$ fulfils the Laue condition for the first-order diffraction at the array of the scatterers with period L_i, $k_{||} = 2\pi/L_i$, it can undergo such diffraction. In terms of band model, this electron would be then transferred into the roughness-induced i-th satellite subband. These satellite subbands are built of the states split off from the principal subbands of the quantum well and are uplifted with respect to the latter. Thus, even when DBRTD is biased beyond its principal resonance peak, electrons can still tunnel from the emitter into the satellite subbands without violation of the in-plane-momentum conservation rule.

SEMICONDUCTOR LASERS CONTROLLED BY ELECTRON EXTRACTION VIA RESONANT-TUNNELING STRUCTURE

V. Ryzhii, I. Khmyrova and M. Ryzhii
Computer Solid State Physics Laboratory, University of Aizu
Aizu-Wakamatsu City, 965-80, Japan

Electron extraction and injection effects in three-terminal semiconductor lasers can be used not only for the control of the concentration of the electron gas in the active region but also for its rapid heating. As the optical gain strongly depends on the electron temperature this mechanism results in a high-speed control of laser generation. The three-terminal laser with the band diagrams shown in figure is considered theoretically. It is supposed that the applied voltage V_P provides the injection of the electrons and holes into the active region while the controlling voltage V_C applied to the RTS affects the electron extraction from this region. The physical origin of the electron gas heating is associated with the extraction of low energy electrons (cold electrons) from the active region via the RTS. Thus if the RTS is open (see figure) so that the extraction current $J_{RT} \neq 0$ the electron temperature in the active region $T = T_1$ exceeds the temperature in the case when the RTS is closed $T = T_2 < T_1$ (see figure).



An analytical model including the equations for the electron concentration, their effective temperature and the equation for photon density of a lasing mode is developed. Using this model the frequency dependence of modulation efficiency is calculated. It is shown that the electron extraction via the RTS can result in an effective and rapid modulation of the laser radiation. The bistability effect in the lasers under consideration connected with the electron charge accumulation behind the RTS is also investigated.

TUNING THE INTER-SUBBAND TUNNELLING AND UCF WITH AN IN-PLANE MAGNETIC FIELD IN THE 'QUANTUM TRANSPORT REGIME'

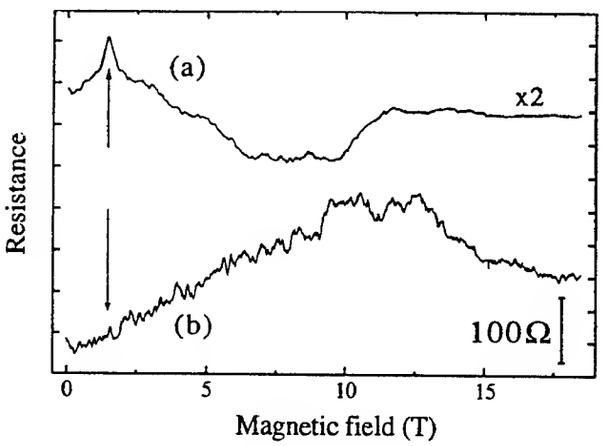
M.J. Gompertz, T. Ihn, A. Nogaret, P.C. Main, L. Eaves, M. Henini, and S.P. Beaumont†

Department of Physics, University of Nottingham, Nottingham, NG7 2RD, UK.

†*Department of Electric and Electronic Engineering, University of Glasgow, Glasgow, G12 8QQ, UK.*

We report electrical transport measurements on a system of parallel 2D electron gases (2DEGs) confined on opposite sides of a single quantum well. By applying a magnetic field in the plane of the quantum well we have been able to 'tune' the tunnelling between the 2DEGs and we observe a *resistance resonance* analogous to that seen in gated devices at zero magnetic field[1]. Recently, Vasko *et al.*[2] have pointed out that parallel 2DEGs, separated by a potential barrier, are an excellent system for studying the 'quantum transport regime' where $\Delta_{SAS} \sim \hbar/\tau$ (Δ_{SAS} is the symmetric-antisymmetric energy splitting and τ is a transport scattering time).

We explore this regime in two ways. First, we study the effect of increasing the disorder by fabricating mesoscopic wires. We find that the resistance resonance is quenched by the disorder (see Figure). In addition, in the mesoscopic wires we are able to observe Universal Conductance Fluctuations (UCF) when the magnetic field is applied *in the plane* of the quantum well. For independent 2DEGs no UCF would be observed in this geometry. We interpret the fluctuations in terms of the dynamics of the tunnelling electrons.



Magnetoresistance (B in plane) of two wires of lithographic wire dimensions (a) 1000nm length x 800nm width, (b) 500nm x 400nm.

[1]A.Palevski *et al.*, Phys. Rev. Lett. **65**, 1929 (1990). [2]F.T. Vasko *et al.*, Phys. Rev. B **52**, 16349 (1995).

STUDY OF RANDOM TELEGRAPH SIGNALS IN A GaAs/AlGaAs SINGLE-ELECTRON TRANSISTOR

T. Sakamoto and K. Nakamura
NEC Fundamental Research Laboratories, 34 Miyukigaoka, Tsukuba, Ibaraki 305, Japan

Single-electron transistors have a high sensitivity for detecting a charge. When the traps having ênergy levels within a few $k_B T$ of the Fermi level exist around the transistors, the current through the transistor shows random telegraph signals (RTSs) caused by capture or emission of single electrons into or from the trap. Although RTS has been observed in numerous single-electron transistors, it has not been characterized systematically. We report the first systematic investigation of single-carrier traps in a single-electron transistor fabricated in a GaAs/$Al_xGa_{1-x}As$ heterostructure. We obtain the distributions of RTSs with changing a bias voltage on a split gate, and show that they describe the positions and energy levels of the individual traps.

A two-dimensional electron gas in the heterostructure has a carrier density of 3.3×10^{15} m^{-2} and a mobility of 110 m^2/Vs. An isolated island with a diameter of 0.6 μm was formed by negatively biased split-gates on the surface of the sample. The current was measured with a constant source-drain voltage of 0.2 mV at a temperature of 50 mK.

Coulomb blockade (CB) oscillations due to successively incrementing single electrons to the island are observed with biasing a voltage on one of the gate electrodes. Further, RTSs are superimposed on the CB oscillations at several gate voltages. The RTS amplitude relative to the total current reaches up to 80 %. These RTSs comprise two kinds of fluctuations: One is the fluctuation in the phase of CB oscillations. The total island charge changes by a fractional charge induced by the trapped charge. The charge fluctuations up to $0.22e$ are observed. The other effect is the fluctuations in the amplitude of the CB oscillations. The trapped charges modify the potential shape around the tunnel barrier by their Coulomb potential, resulting in the variation of the tunnel conductance.

The current through the island is measured with changing V_L and V_R, which are the bias voltages on the gates in the left and right side of the island. The points where the current fluctuations are larger than measurement noise level are plotted in a (V_L, V_R) plane. This plot clearly shows the distributions of RTSs. The (V_L, V_R) values at RTSs are related to the energy levels of the traps. The set of the points, which consist of RTSs caused by a specific trap, forms a line in the (V_L, V_R) plane. The slope of the line depends on the distance from the gate to the trap, which suggests spatial distributions of the traps. Moreover, there are several lines with the same slopes. Possible explanation is that a single trap, which may have multi-levels with certain energy separations, is a source of these RTSs.

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NONLINEAR OPERATION OF FINITE-SIZE TUNNEL JUNCTION BETWEEN 2D ELECTRON SYSTEMS

O. E. Raichev and F. T. Vasko

Inst. of Semiconductor Physics, Pr.Nauki 45, 252650, Kiev, Ukraine

Direct investigation of the tunneling current between two-dimensional (2D) electron layers became possible since the advent of independently contacted double quantum well systems [1] (DQW's). This current strongly depends on the level splitting energy Δ in the vicinity of the tunnel resonance ($\Delta \sim 0$). The value of Δ can be controlled either by side-gate bias or by interlayer bias eV applied to the contacts. In the last case, application of sufficiently large voltage V transfers the system into a nonlinear regime of operation, when its tunnel conductance considerably depends on V. We study the nonlinear operation of independently contacted DQW's under the longitudinal size effect regime [2], when a competition between the tunneling current and in-plane currents leads to inhomogeneous distributions of the potentials in the wells along the DQW's plane. This situation realizes when the length L of the DQW's becomes comparable with the square root from the ratio of the averaged in-plane conductivity σ to the tunnel conductance G. Under such conditions, local interlayer voltage v depends on in-plane coordinate $\mathbf{x}$ according to the following nonlinear equation

$$\sigma \frac{\partial^2 v(\mathbf{x})}{\partial \mathbf{x}^2} - 2G[v(\mathbf{x})]v(\mathbf{x}) = 0,$$

where local tunnel conductance $G[v]$ depends on v in a resonant way [3]. Boundary conditions to this equation are determined by proper geometry of contacting to the 2D layers. We solve the problem for the case of one-dimensional inhomogeneity. Numerical results are presented for parameters of DQW's from Ref.[4], where the size effect has been observed in the linear regime [2]. Calculated current-voltage characteristics of the DQW's are nonlinear and show S-shape behavior at negative Δ, reflecting formation of *bistable patterns* of the potentials and currents in the 2D plane.

[1] J. P. Eisenstein, Superlattices and Microstructures, **12**, 107 (1992).

[2] F. T. Vasko, Appl. Phys. Lett. **68**, N 3 (1996); O. E. Raichev and F. T. Vasko, Phys. Rev. B, submitted.

[3] F. T. Vasko and O. E. Raichev, JETP, **81**, 1146 (1995).

[4] N. K. Patel, E. H. Linfield, *et. al.*, Appl. Phys. Lett. **64**, 3018 (1994).

Coherent Bloch-Phonon Oscillations in Semiconductor Superlattices

T. Dekorsy, G.C. Cho, A.M.T. Kim, K. Köhler*, and H. Kurz

Institut für Halbleitertechnik, RWTH Aachen, Sommerfeldstr. 24, D-52056 Aachen, Germany

*Fraunhoferinstitut für Angewandte Festkörperphysik, D-79108 Freiburg, Germany

Bloch oscillations in semiconductor superlattices have attracted great interest since their first time-resolved observation in femtosecond time-resolved optical experiments. The investigation of Bloch oscillations allows to determine the influence of Wannier-Stark localization on the dynamics of coherent electronic wavepackets, the amplitude of the oscillations, and gives insight into the relevant dephasing processes. These studies have lead to the observation of Bloch oscillations at room-temperature in the range of 4 THz to 8 THz. Since electronic phenomena in polar semiconductors are mainly governed by the interaction of the charge carriers with polar lattice vibrations, the investigation of the interaction of Bloch oscillations with LO phonons in superlattices is of prime importance. Here we report on the first direct observation of the coupling between coherent electronic wave packet oscillations with LO phonons. The experiments are performed on a $GaAs/Al_{0.3}Ga_{0.7}As$ superlattice with a first electronic miniband width of 36 meV by time-resolved reflectivity and electro-optic spectroscopy with pulses of 50 fs duration (40 meV spectral width). The optical pulses initially create a coherent superposition of Wannier-Stark levels performing Bloch oscillations in the biased superlattice. When the frequency of the Bloch oscillations is tuned into resonance with the optical phonon, we observe a coupling characterized by an avoided crossing of the Bloch frequency with the phonon resonance. In addition, the dephasing of the coherent amplitude is slowed down. These results indicate that Bloch oscillations and LO phonons are coupled via an electric field with the consequence that the slower dephasing of the lattice vibrations stabilizes the electronic coherence. This stabilization is an essential condition to resolve Bloch-phonon coupling at room temperature.

Dynamical Localization and Stimulated Absorption and Emission Induced by a THz Field in a Double Quantum Well

Ramón Aguado and Gloria Platero

Instituto de Ciencia de Materiales (CSIC), Cantoblanco, 28049 Madrid, Spain.

We analyzed theoretically the I-V characteristic of a double quantum well integrated in an antenna and driven by THz radiation. The n-doped sample consists in a triple barrier of $Al_{.3}Ga_{.7}As$ and a double well of GaAs. We have studied, within the Transfer Hamiltonian framework, the effect that the AC field produces on the tunneling current through the sample. We have performed a selfconsistent calculation in order to evaluate the sequential current where the electron-electron interaction is treated in a mean field approximation(1) and where temperature and scattering effects are also discussed. In the presence of an AC field, the wave function develops side bands which are traduced in satellite peaks in the spectral density (2). The tunneling current takes place due to the alignment of these side bands of the different spatial regions. Additional features in the current density appear due to these new effective channels whose intensity and position in bias depends on the frequency and intensity of the external AC field and on the charge accumulated in the wells. We have observed some interesting physical features : for some intensities and frequencies of the field quenching of the transmission and therefore quenching of the main peak of the current .Also we observe, in the linear response regime absolute negative conductance. This fact, already observed in superlattices(3), is explained by means of our model. We compare our calculations with recent experimental information of the photoassisted current through a double well (4).

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Franz - Keldysh oscillations at the miniband edge in a GaAs/$Al_xGa_{1-x}As$ superlattice

M. Ando, M. Nakayama, H. Nishimura, H. Schneider[A] and K. Fujiwara[B]

Department of Applied Physics, Osaka City University, Sumiyoshi-ku, Osaka 558, Japan
[A]Fraunhofer-Institute für Angewandte Festkörperphisik, D-79108 Freiburg, Germany
[B]Department of Electrical Engineering, Kyushu Institute of Technology, Fukuoka 804, Japan

In a superlattice (SL) with a period D, it is well known that the mini-Brillouin-zone formation results in the minibands of electrons and holes. Recently, the effects of external electric field, F, have been studied considerably in SL's; Franz-Keldysh (FK) oscillation and Wannier-Stark (WS) localization. In a weak electric field regime, it is expected that the FK oscillations are observed at the critical points of the joint density of states (JDOS) in optical transitions. In the present work, we have focused on the FK oscillations at the miniband edge in a GaAs (7.0nm) / $Al_{0.1}Ga_{0.9}As$ (3.5nm) SL.

Figure 1 shows the electroreflectance (ER) spectra at various electric fields. The arrows located on the ER spectrum at F = 4 kV/cm indicate the interband transitions calculated by the Kronig-Penny model at F = 0. The notation of H11 (L11) denotes the interband transition with the n = 1 electron and n = 1 heavy (light)- hole minibands, and Γ and π indicate the transitions at the Γ point (miniband center; k_z = 0) and the π point (miniband edge; $k_z = \pi/D$), respectively. From the calculated transition energies, it is evident that ER spectrum at 4 kV/cm reflects the miniband structure. Noticing the H11(π) transitions at F = 4 kV/cm, we clearly observe the oscillatory structure (the indices 0-7) toward the low energy side. Since the miniband edge is the M_1 critical point of three-dimensional (3D) JDOS, so-called a saddle point, it is expected that the direction of the FK oscillation is the low energy side of the H11(π). Thus, the above oscillatory structure results from the FK oscillations at the miniband edge. From Figure 1, it is obvious that the direction of the FK oscillations changes at F = 15 kV/cm. It is noted that the ER spectra above F = 15 kV/cm exhibits the characteristics of Stark ladders (quasi-2D states) due to the WS localization. We consider that the change of the direction of the FK oscillations reflects the transformation of the JDOS dimensionarity from the 3D type to the 2D one. The FK oscillations disappear above F = 24 kV/cm where the electron wavefunction is fully localized in individual quantum wells.

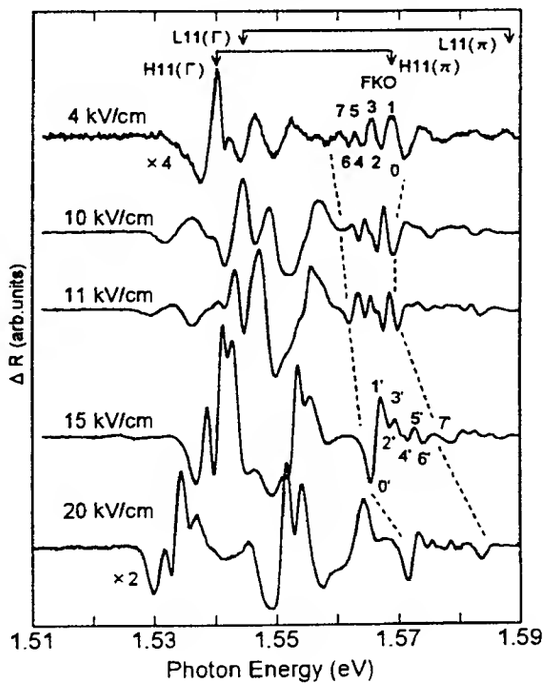

Figure 1. ER spectra of GaAs (7.0nm) / $Al_{0.1}Ga_{0.9}As$(3.5nm) at various electric field.

Theoretical studies of subband carrier lifetimes in an optically pumped 3-level asymmetric quantum well terahertz laser

P. Harrison and R. W. Kelsall

Department of Electronic and Electrical Engineering,

University of Leeds, LS2 9JT, U.K.

The importance of intersubband transitions as a means of generating electro-magnetic radiation has been vividly demonstrated with recent advances in mid-infrared lasers[1]. The purpose of this work is to present a theoretical feasibility study of taking the intersubband technology to wavelengths longer than the far-infrared.

Calculations of subband lifetimes are presented for a system based on the optically pumped 3-level asymmetric quantum well laser design of Berger[2]. The structural parameters have been adjusted in order to vary the $E_3 \longrightarrow E_2$ radiative transition from 3 THz to 8 THz, whilst keeping the pump transition energy ($E_1 \longrightarrow E_3$) fixed at the CO_2 laser line of 10.6 μm. For this frequency range, the $E_3 - E_2$ subband edge separation is less than the LO phonon energy in GaAs. Consequently, terahertz lasers based on this design will exhibit enhanced radiative efficiencies, due to the suppression of non-radiative LO phonon emission. On the other hand, the $E_2 - E_1$ separation exceeds the LO phonon energy, resulting in fast depopulation of the E_2 state—a key feature in attaining population inversion. Our results are compared with intersubband lifetimes in square quantum wells, to identify the influence of the asymmetric geometry.

In addition, a four level asymmetric quantum well system is studied, in which the radiative transition ($E_4 \longrightarrow E_3$) is followed by fast LO phonon emission into an intermediate state E_2. The $E_3 \longrightarrow E_2$ separation is tuned exactly to the LO phonon energy, giving rise to near-vertical transitions for which the phonon emission probability is maximised. Hence this configuration offers further potential for the attainment of population inversion in an intersubband quantum well laser.

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Dynamics of strongly driven two-level systems: Analytical solutions

Mathias Wagner[a] and P. Vasilopoulos[b]
a) Hitachi Cambridge Laboratory, Madingley Road, Cambridge CB3 0HE, United Kingdom
b) Concordia University, Dept. of Physics, 1455 de Maisonneuvre Blvd. West., Montreal, Canada, H3G 1M8

The high switching speed envisaged in future electronic circuits necessitates a treatment of time-dependent effects beyond the traditional adiabatic approach and is, furthermore, likely to occur with high amplitudes comparable to typical energies in the devices. This renders pertinent further studies of quantum-mechanical systems driven by strong time-dependent electric fields which are known to lead to unusual effects such as the "coherent destruction of tunneling"[1] or a strong quenching of the transmission probability in large-area resonant tunneling diodes[2]. In this work the dynamics of a strongly driven two-level system, as realized, e. g., in a double quantum well with only the lowest two electronic levels occupied and driven by a strong laser field or by two phase-shifted oscillating gate voltages, is studied analytically and numerically. *Analytical* solutions are *known only for very weak*[3] *or strong*[4] *driving fields* F. Here, in addition to the *exact numerical* solution, we present an **analytical iterative** solution, *valid for arbitrary* F, of the time-dependent Schrödinger equation of the driven two-level system. The procedure yields not only successively improved approximations to the quasi-eigenenergies but also to the state vectors. Its convergence is determined by the ratio of the photon energy $\hbar\omega$ to the level splitting $2\hbar\omega_0$ in the absence of driving (F=0). Figure 1 shows the energy of one of the two levels as a function of F, backfolded in the *Brillouin zone* of this Floquet state. The solid, dashed, and dotted curves represent, respectively, our *exact numerical*, the *strong field*[4], and our **analytical** solution after two iteration steps. Despite the rather large value chosen for ω_0/ω, the improvement in accuracy is quite good, in particular at the roots of $\varepsilon(F)$=0, where "coherent destruction of tunneling" between the two levels occurs[1]. Utilizing the nonlinearity of $\varepsilon(F,\omega)$, a potential application of this behaviour is a couple of pairs of quantum dots having different dipole moments serving as an *integrated* detector for *amplitude* **and** *frequency* of external radiation. Such a device would even be sensitive to the *polarisation* of the radiation. This work was performed under the management of FED as a part of the MITI R&D Program (Quantum Functional Device Project) supported by NEDO.

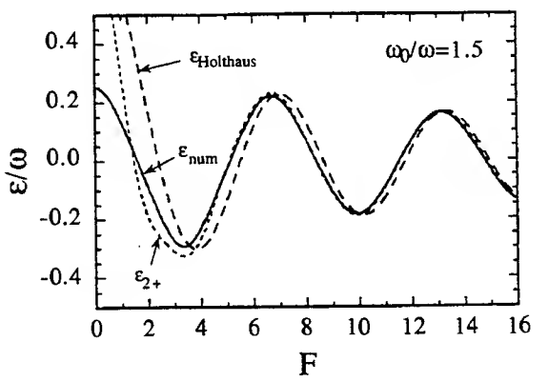

Fig. 1: Quasi-eigenenergy of one of the two levels as a function of driving field.

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Theory of Electron Transport in a THz-Field Irradiated Semiconductor Superlatttice: Occurrence of Quantized DC Voltages and Current Responsivity

A.A. Ignatov[1)], E. Schomburg[1)], J. Grenzer[1)], S. Winnerl[1)], K.F. Renk[1)] and E.P.Dodin[2)]

[1)]Institut für Angewandte Physik, Universität Regensburg, 93040 Regensburg, Universitätsstr. 31 Germany; [2)], Institute for Physics of Microstructures, RAS, N. Novgorod, Russia

We analyse theoretically the THz-field induced nonlinear response of electrons capable to perform Bloch-Zener oscillations in a semiconductor superlattice (SL) [1]. We predicted [2] that for a strong THz-field, similar to the inverse ac Josephson effect, quantized dc voltages close to $V_{dc} = Nn\hbar\omega/e$ should occur in the irradiated SL due to multiphoton resonances $\Omega_B = eE_0d/\hbar \approx n\omega$ even at room temperature if $\omega \geq \nu$ (where ω is the frequency of the THz-field, N the number of the SL periods, n the integer, E_0 the dc electric field, d the SL period, Ω_B the Bloch frequency, ν the average intraminiband scattering frequency).

In this paper we apply the approach developed in [2] to calculation of the current responsivity (current change per absorbed power) for this photon-assisted process in the limit of a small radiation signal and find:

$$R_i = -\frac{e}{N\hbar\nu}\frac{Z(3+\alpha^2-Z^2)}{(1+Z^2)(1-Z^2+\alpha^2)}$$

where $Z = E_0/E_c = \Omega_B/\nu$, $\alpha = \omega/\nu$ and $E_c = \hbar\nu/ed$ is the critical field of the Esaki-Tsu dc current voltage characteristic. For $E_0 \leq E_c$ and at $\omega \gg \nu$ (THz-frequency band) $R_i \approx -e/(2N\hbar\nu)$ does not depend on frequency within the limits of semiclassical approximation $\hbar\omega \leq \Delta$ (where Δ is the SL miniband width). We thus obtain $|R_i| = [e/(\hbar\omega)]\cdot[\hbar\omega/(2N\hbar\nu)] \leq [e/(\hbar\omega)]\cdot[\Delta/(2N\hbar\nu)]$. This shows the maximum responsivity $|R_i^{max}| = e/(2\hbar\omega)$ for the minimum number of the SL periods $N_{min} = \Delta/(\hbar\nu)$ which is restricted from below by the spatial amplitude of the Bloch oscillations $X_B = \Delta/(eE_c) < Nd$.

We suggest that for a short SL $N \geq N_{min} = \Delta/(\hbar\nu)$ and for THz-frequencies $\nu < \omega < \Delta/\hbar$ the responsivity R_i can be quite comparable to the quantum efficiency $e/(\hbar\omega)$ if the rf impedance of the device is matched to that of the THz-field antenna and that SL devices can be used for developement of novel high-sensitive THz-field detectors operating at room temperatures.

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Abstract for Ninth International Conference on Superlattices, Microstructures and Microdevices, Liege, Belgium

L. Friedman and R.A.. Soref, Rome Laboratory/EROC , Hanscom AFB, MA 01731, and G.Sun, Engineering Program, University of Massachusetts, Boston, MA 02125

Intersubband Lasing in Silicon-Based Quantum Well Structures.

Because strong polar optical phonon scattering is absent in SiGe/Si, the lifetime difference (τ_u-τ_l) between the upper and lower lasing subband levels, to which population inversion and laser gain are proportional, is an order of magnitude larger for SiGe/Si quantum well structures than for the III-V semiconductors. Also, (τ_u-τ_l) remains positive even when the subband energy difference exceeds an optical phonon energy. The lifetimes are further enhanced by a factor of two to four due to optical phonon confinement. We consider (a) SiGe wells confined by Si barriers for intersubband lasing at 5 - 10 μm , and (b) Si wells confined by high barrier materials such as ZnS at 1.55 μm . For case (b), the required high electric fields and applied voltages suggests parallel operation in a pipi (or nini) structure with selective contacts, rather than a series cascade structure. In addition to operation in the Si valence band, the Si conduction subbands can be utilized, taking account of the strong band nonparabolicity. Normal incidence emission is expected for (111) and (110) surfaces.

FUNCTIONAL PROPERTIES OF LUMINESCENT POROUS SILICON AS A COMPONENT OF OPTOELECTRONIC INTEGRATION

M. Araki, T. Ozaki, X. Sheng, H. Koyama and N. Koshida

Division of Electronic and Information Engineering., Faculty of Technology, Tokyo University of Agriculture and Technology, Koganei, Tokyo 184, Japan

The applicability of luminescent porous Si (PS) to optoelectronic integration has been studied from the following two different viewpoints. (a) Design and fabrication of Si microphotonic devices; (b) Finding of novel functions of light-emitting PS diodes.

The concept of PS photonic devices is based on precise control of refractive index of PS. The optical waveguide, for instance, is composed of an upper-side cladding layer (a thin Al film), an active PS layer, and a lower-side cladding PS layer. The optical cavity consists of a thin Ag film mirror, an active PS layer, and a quarter-wavelength PS multilayer mirror. In these devices, the stacked PS layers are formed on Si substrates simply by modulating the anodization current density.

When excited by an Ar or He-Cd laser from above, the respective devices operate as an edge-emitting waveguide and a vertical microcavity. The light wave is confined enough in the PS waveguide, and the output light emitted from the cleaved facets of the device is significantly and automatically polarized along the TE mode direction due to the metal cladding layer, as expected from the analytical simulation. The PS cavity, on the other hand, acts as a Fabry-Perot resonator, and the significantly narrow PL spectra (the minimum width: 6 meV in FWHM) can be tuned over a wide range of the visible region by changing the design parameters.

In the light-emitting PS diodes consisting of thin Au films, PS layers, and n- or p-type Si substrates, we have observed some characteristic features related to the properties of PS as a nanocrystalline system. Especially of importance are the reversible field-induced PL quenching effect, the electrical behavior like an MIS tunnel diode, and the cold electron emission through the thin Au film during the operation of light emission.

These results suggest that PS microstructures are useful for Si-based optoelectronic integration with various combined functions.

BALLISTIC TRANSPORT IN QUANTUM CYLINDERS

A.V.Chaplik, D.A.Romanov, L.I.Magarill

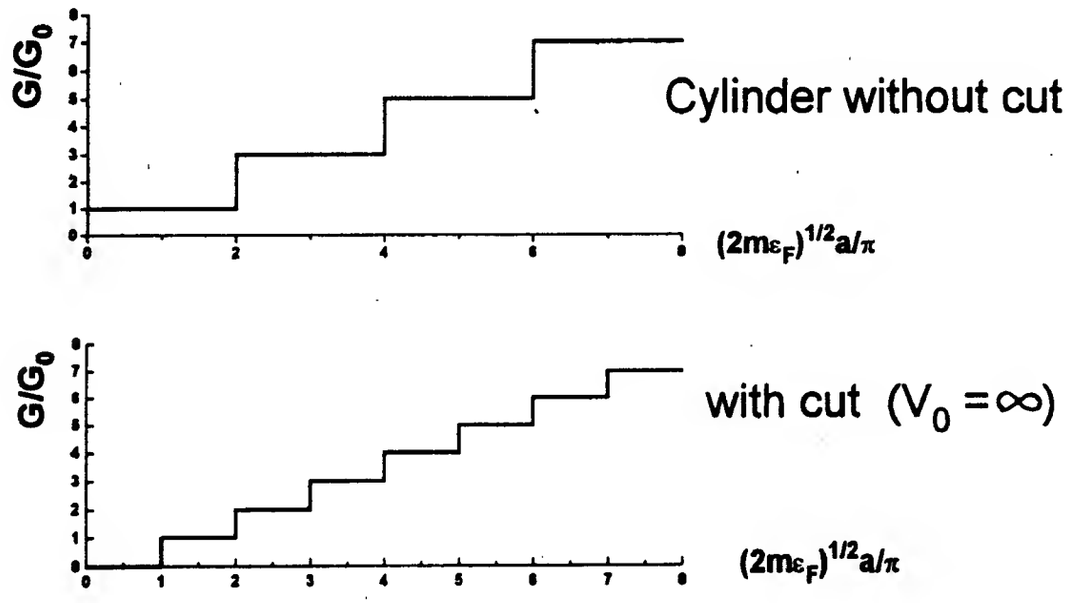
Institute of Semiconductor Physics, Novosibirsk, 630090, Russia

We present a theoretical study of the ballistic conductance of hollow quantum wires made of two-dimensional electron gas placed at a cylinder surface. The picture of the conductance dependence on the Fermi energy ε_F differs drastically from the conventional case of the strip-like wire with the width equal to the cylinder perimeter a. We trace the evolution of the difference between these two cases on the model of circular cylinder affected by δ-like potential barrier to simulate the "cut" of the cylinder along its element.

The conductance dependence of the initial cylinder begins with finite value $G = G_0 = 2e^2/h$ and demonstrates quantum steps of the height $2G_0$. At a finite δ-function amplitude V_0 each step splits in two steps of the equal height G_0. With increasing V_0 the distance between steps in each pair also increases. Finally they tend to be equidistant in the Fermi momentum scale resulting in the conventional picture of the strip-like wire conductance (provided the strip width equals a; see Figure).

We have also considered a more realistic case of the cylinder with two diametrically opposite δ-functional barriers. In this case the evolution of the conductance leads to restoration of the initial picture but shifted G_0 downward. Such a situation can be realized experimentally in semiconductor heterostructures: a sandwich of two quantum strip-like wires connected by tunneling across their edges.

The revealed difference of G_0 between the conductances of quantum strip and quantum cylinder holds when the transversal size of the wire tends to infinity. This means that (contrary to the common opinion) the difference between periodic and zero boundary conditions causes finite and physically observable consequences.



Conditions for Direct Band-Gap in Si Quantum Wires

Seiji Horiguchi

NTT LSI Laboratories, 3-1 Morinosato Wakamiya, Atsugi, Kanagawa, 243-01 Japan

Some theoretical papers have shown that the quantum confinement of Si wire with direct band-gap can explain the strong visible light luminescence from porous Si[1]. However, most of those papers considered only <100> oriented rectangular wires; it has not yet been shown theoretically in which direction and with what cross sectional shape Si wires have a direct band-gap. Therefore, we have investigated this condition systematically and have shown that not only <100> oriented wires but also other wires on the {100} plane have a direct band-gap. This is different from the finding of Filonov et al.[2] that only <100> oriented wires have a direct band-gap.

We consider a Si wire whose cross sectional length is shorter than the coherence length. The condition in which the Si wire has a direct band-gap is that the minimum energy of electrons exists at the Γ point, because the maximum energy of holes always exists at the Γ point. We have investigated this condition within the effective mass theory, the validity of which for Si quantum wires has been confirmed[3]. The method of obtaining the energy eigenvalues of electrons in Si wires with arbitrary cross sectional shapes and wire directions is a generalized one from our previous work[4]. We have taken into account the six anisotropic valleys near the X points in bulk Si in solving the effective mass equation. The height of the confinement potential was assumed to be infinite. The results are summarized below.

Only Si quantum wires on the {100} plane can have a direct band-gap. In particular, <100> oriented Si quantum wires have a direct band-gap regardless of their cross sectional shapes. For wires other than <100> oriented ones, we have investigated the condition for rectangular, elliptic, triangular and trapezoidal cross sectional shapes. In all cases, the band structure of a wire changes from indirect to direct as the height of the wire (the size perpendicular to the {100} plane) becomes low enough compared with the width (the size parallel to the {100} plane). Moreover, <110> oriented wires have the largest ratio of the height to the width for a direct band-gap.

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Quantum Tunnel Reflectors and Superlattices on Their Basis.

Z.S.Gribnikov, A.N.Korshak, N.Z.Vagidov,

Institute of Semiconductor Physics of Ukrainian National Academy of Sciences,

45 pr. Nauki, Kyiv-28, 252650, Ukraine.

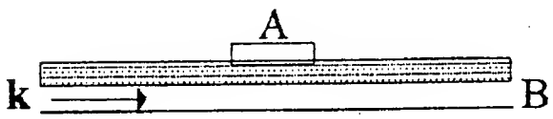

Fig 1

According to our interpretation a quantum tunnel reflector (QTR) is a finite fragment (A) of an electron waveguide (EWG) which is tunnel-coupled with an infinite EWG (B) in which we consider an electron wave propagation (Fig. 1). Considered models of QTR are the following: *(a)* a tunnel contact of a quantum wire (B) with a finite fragment (A) of the same wire; *(b)* a tunnel intersection of a quantum wire (B) with another one (A) oriented at right or oblique angle to (B); *(c,d)* a tunnel contact of a quantum well (B) either *(c)* with a strip - line fragment of the similar well (A) (that is with a real quantum wire) or *(d)* with a round fragment of the well (A) (that is with a real quantum dot). (The cases *(c)* and *(d)* were considered before in [1, 2]). It is shown the QTRs are very effective tunnel reflectors of electron waves in EWG and can be used as controlling device elements.

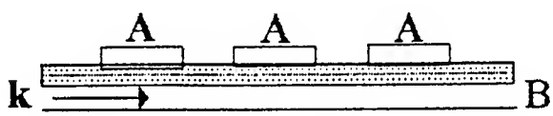

Fig 2

Dispersion relations $\varepsilon(\mathbf{k})$ of 1D- (and 2D- in the case *(d)*) superlattices which are obtained as a result of periodical repetition of a QTR - cell (Fig. 2) are considered. It is shown these spectra are effectively controlled by a transverse electric field. Different realizations of the QTR - superlattices are discussed, including self - assembled arrays of quantum wires and quantum dots.

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The Optical Absorption of Quantum-Well Wires

S. Glutsch,[1,2] F. Bechstedt,[1] and D.S. Chemla[2]

[1] *Friedrich-Schiller-Universität Jena, Institut für Festkörpertheorie und Theoretische Optik*

[2] *Department of Physics, University of California at Berkeley*
and Material Sciences Division, Lawrence Berkeley National Laboratory

We calculate, for the first time, the optical absorption of quantum-well wires, taking into account Coulomb interaction, unequal effective masses, and continuum states. We present optical absorption spectra and exciton binding energies for a large variety of wire widths, lengths, thicknesses, and band offsets.

We observe a gradual transition from a two-dimensional to a one-dimensional semiconductor as the wire width is reduced and a transition from a one-dimensional to a zero-dimensional semiconductor as the lengths is reduced. By comparison of different effective-mass ratios we rigorously show that, even for small wire widths, the dominant features of the spectrum stem from the center-of-mass motion of the exciton. Absorption lines, which are forbidden in the interaction-free case, appear in the optical spectrum as a result of Coulomb coupling and exhibit a Fano line shape.

We also study shallow quantum wires, i.e., quantum wires with extremly small barrier heights, and quantum-well-wire arrays. A comparison of the binding energies vs. the characteristic length is made for quantum-wells, quantum-well wires, and quantum dots. We examine the validity of the one-subband approximation. This model is found to correctly describe the extreme one-dimensional limit, but breakes down for realistic wire widths.

OPTICAL PROPERTIES OF THE SEMICONDUCTOR AND METAL QUANTUM WIRES IN THE CHRYSOTILE ASBESTOS NANOCHANNELS.

V.V.Poborchii

Ioffe Physico-Technical Institute, St.Petersburg 194021, Russia

The chrysotile asbestos (composition $Mg_3Si_2O_5(OH)_4$) consists of the closely packed nanotubes with external diameters 20-30 nm and internal diameters 2-10 nm. Being transparent for the visible light, the chrysotile asbestos is very attractive for the preparation of the quantum wires inside nanotubes and studying their optical properties.

A variety of semiconducting and metallic materials has been incorporated into the chrysotile asbestos channels using different methods. Materials with the low melting temperature have been incorporated by imbibition under the high pressure, and materials with the high melting temperature have been incorporated by means of the chemical synthesis inside channels. Clear transmission electron microscopic images of the incorporated wires have been obtained.

Polarized optical absorption and Raman spectra of the asbestos containing the wires have been studied. A high absorption anisotropy associated with the difference between the depolarization factors for the light polarized parallel and perpendicular to the wires has been observed for both semiconducting and metallic materials. The features associated with the transitions between the size-quantized bands has been observed for $A^{III}B^{V}$ and $A^{II}B^{VI}$ semiconducting quantum wires. Amorphization of some materials in the asbestos channels has been found.

MAGNETOOSCILLATIONS IN A TRAPEZOIDAL TWO-DIMENSIONAL ELECTRON GAS GROWN OVER GaAs WIRES.

G.M. Gusev[1], N. La Scala Jr.[1], D.I. Lubyshev[1], P.P. González-Borrero[1],

M.A.P. da Silva[1], J.C. Rossi[2] , J.C.Portal[3] , P. Basmaji[1]

[1]Instituto de Fisica de São Carlos, 13560-970, Universidade de São Paulo, SP, Brazil

[2]Universidade Federal de São Carlos, São Carlos, SP, Brazil

[3]CNRS-LCMI, F-38042, Grenoble and INSA-Toulouse, 31077, France

In the present work we realized a non planar structure containing a two-dimensional electron gas (2DEG) for studying the behaviour of electrons at random and sign alternating magnetic field. Samples were fabricated employing overgrowth of GaAs and AlGaAs materials by molecular beam epitaxy on pre-patterned GaAs substrate. The pre-patterning is consisted of wires produced by electron beam lithography at the center of a conventional Hall bar. After selective deep wet etching, several wires with trapezoidal shape (diameter 0.5-1 μm and length 10 μm) were created. Since the 2D electrons are sensitive only to the normal component of B, they will move in an positive or negative magnetic field, depending on their position on trapezoidal planes and the angle between magnetic field and substrate ϕ. In magnetic field perpendicular to the substrate plane, large positive magnetoresistance and Shubnikov oscillations have been observed. The effects on the Shubnikov oscillations, by changing of a specific realization of an inhomogeneous magnetic field, were studied by measuring the magnetoresistance for different angles ϕ. We found that at low magnetic field, positions of Shubnikov oscillation peaks follow $B_p \sim B\sin(\phi-\theta)$, where θ is the angle of plane ($\sim 15^{\circ}$) containing electrons, which contribute to the magnetoresistance. At strong magnetic field, oscillations change the phase and exhibit additional structure, which are originated from complexity of the magnetotransport in the inhomogeneous field.

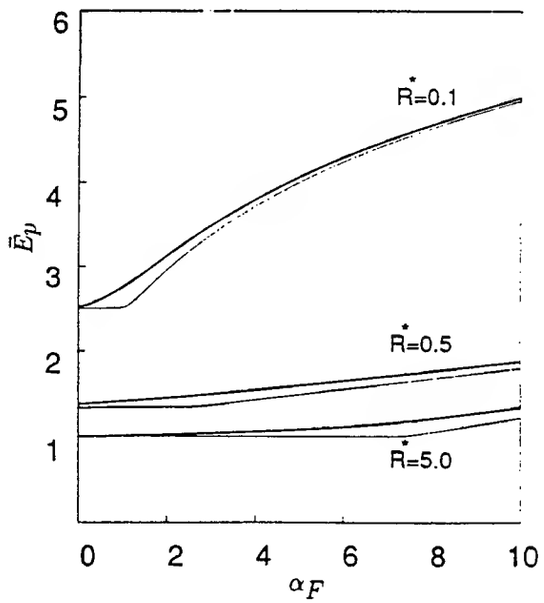
ELECTRON-PHONON PHENOMENA IN CYLINDRICAL AND PLANAR QUANTUM WIRES

E. P. Pokatilov*, V. M. Fomin*,**, S. N. Klimin*, J. T. Devreese**, S. N. Balaban*, L. C. Fai*

*State University of Moldova, str. Mateevici, 60, 277009 Kishinev, Republic of Moldova

**Universiteit Antwerpen (U.I.A.), Universiteitsplein, 1, B-2610 Antwerpen, Belgium

The ground state energy, effective mass and other polaron parameters are investigated as a function of the electron-phonon coupling constant α_F for quasi 1D quantum wires (QW) of two types: cylindrical and planar, which differ from one another by minimal and maximal surface area per unit length, respectively. Polaron parameters in QW's of other types are expected to take intermediate values between those specific for the structures considered here. In the cylindrical QW, electron confinement is imposed by a parabolic potential with axial symmetry, whereas in the planar QW a 1D parabolic potential is acting along the X axis. Varying the parameters characterizing the parabolic potentials, we can change the effective radius R in the cylindrical QW, and the width of the electron localization region $L_x = L$ in the planar QW. As far as there are no interfaces in the cylindrical system with the parabolic potential, it is reasonable to consider the electron-phonon interaction with 3D bulk phonons only. In the planar QWs, both bulk-like and interface phonons are taken into account. Within two approaches: (i) Feynman variational principle (FVP) and (ii) interpolation variational theory (IVT), the polaron ground state energy, the polaron effective mass, the inverse radii of polaron states, the average number of phonons in the polaron clouds were calculated as a function of α_F and R (L). The following results are obtained for the dimensionless polaron binding energy $\bar{E}_p(\alpha_F, R^*(L^*))$, where $\bar{E}_p = (\varepsilon_p - \varepsilon_{sq})/\alpha_F\hbar\omega_0$, ε_p is the total polaron energy, ε_{sq} is the size quantization energy, ω_0 is the longitudinal optical phonon frequency, $R^* = R/R_p$, $L^* = L/R_p$, $R_p = (\hbar/2m\omega_0)^{1/2}$. For decreasing $R^*(L^*)$, the boundary of the weak coupling region ($\bar{E}_p$ = const) shifts to smaller values of α_F, so that in the limit $R^*(L^*) \to 0$ the weak coupling regime vanishes. These peculiarities of the function $\bar{E}_p(\alpha_F, R^*)$ are presented in the figure, where heavy and thin lines correspond to FVP and IVT, respectively. At finite α_F, analytical formulae for the polaron energy and mass are obtained which turn out to be the same for both calculation methods. The polaron energy is described by the nonlinear equation $y = -q \ln y$, where y is proportional to $\bar{E}_p^{1/2}$ and q is proportional to α_F. At a fixed value of R (L), when α_F increases, the energy $\bar{E}_p(\alpha_F, R^*(L^*))$ tends to the limiting 3D value which does not depend on R (L). As a consequence, the conclusion on the absence of the weak coupling regime in 1D QW is obtained using two different models of quasi 1D wires and with two independent theoretical calculation methods.



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Transport Characterization of Quantum Wires by Magnetophonon and Magnetic Depopulation Experiments

G.Ploner, M.Hauser, J.Smoliner, G.Strasser and E.Gornik

Institut für Festkörperelektronik
Mikrostrukturzentrum der TU Wien
Floragasse 7, A-1040 Wien, Austria

On arrays of nanoscale, one dimensional quantum wires the clear resolution of magnetophonon resonances (MPR) has been achieved and could be used for the first time to perform a systematic study of characteristic properties of these systems. MPR result from the resonant scattering of electrons between their confinement induced sublevels by LO phonons at temperatures around 100 K. In a preliminary experiment we verified, comparing the results of magnetic depopulation and magnetophonon effect, that the latter can be used to investigate subband spacings and the polaron mass of electrons in one dimensional systems. This is particularly useful in the case of quantum wires near the quantum limit where traditional methods for the characterization of 1D systems, such as magnetic depopulation experiments, fail due to the low number of occupied subbands. By variation of the electronic density in the investigated quantum wire systems a situation could be achieved where fewer and fewer subbands are occupied. It could be shown that the magnetophonon effect is strongest in those cases where the electron density is so low that the classical magnetic depopulation experiments no longer give reliable information. We showed that the subband spacing in our quantum wire systems raises steeply when the electron density is decreased below approximately $2x10^6$ cm^{-1}. Also it has been found that the polaron mass in 1D systems is enhanced compared to the 2D case and also increases with decreasing electron density in the wire. The latter is clearly due to a stronger electron-LO phonon-coupling resulting from the reduction of screening effects.

In systems containing only few (up to five) ballistic quantum wires which were prepared using electron beam lithography and wet chemical etching additional structures in the magnetoresistance at low magnetic field strengths could be observed. These structures reveal themselves at relatively high current densities to be peaks with additional fine structure superimposed. They could be explained by the assumption that electrons exiting one quantum wire are magnetically focused into the adjacent wire after one or more scattering events from the boundary of the etched region. This coherent focusing leads to interference effects which result in the observed fine structured peaks in the magnetoresistance. In further experiments the dependence of this effect on temperature and the length of the quantum wires will be investigated. It is expected that it can be used as a tool to determine phase coherence lengths in quantum wires.

FOLDED AND CONFINED ONE-DIMENSIONAL PLASMONS IN MODULATED WIRES

Florent Perez[1], Bernard Jusserand[1], Laurence Ferlazzo-Manin[2], Claus Dahl[1], Marcel Filoche[1] and Bernard Etienne[2]

1- France Télécom/CNET/Paris B, Laboratoire de Bagneux, 196 Avenue Henri Ravera, 92220 Bagneux, France

2-Laboratoire de Microstructures et Microélectronique, CNRS, 196 Avenue Henri Ravera, 92220 Bagneux, France

We demonstrate experimentally and theoretically the deep modification of the dispersion of plasmons in quantum wires, when the width of the wires is periodically modulated. We have fabricated modulated quantum wires on a high mobility GaAs-GaAlAs modulation doped heterostructure by deep Reactive Ionic Etching. The obtained profile reproduces well the coded one as illustrated on the SEM micrograph opposite to the right.

The experimental dispersions are determined by Raman scattering experiment in pumped liquid-helium. In the three samples we have prepared, we observe a splitting of the lowest even 1D plasmon mode for a wavevector along the wire corresponding to the zone edge. Its value increases with modulation amplitude. The first odd plasmon mode is dispersionless. We have modelled the experimental results within a classical frame. A new solution of the integro-differential equation of plasmon modes confined in complex geometries is introduced using a basis of local functions. Calculations very well reproduce the experimental data.

This study proves the existence of both confined and folded 1D plasmon modes in modulated wires. It demonstrates the great sensitivity of plasmon dispersions on the detailed boundary conditions and the great ability of deep etching to define such complex profiles allowing a detailed control of the electrostatic boundary conditions at a very low scale (10nm) while preserving the high quality of the initial 2D electron gas.

Self-adjusting formation of a lateral confinement potential in heterostructures with compensating *pn* layers

U. Wieser, S. Skaberna, and U. Kunze

Lehrstuhl für Werkstoffe der Elektrotechnik, Ruhr-Universität Bochum,

D-44780 Bochum, Germany

We have developed a new concept to create a lateral confinement potential in a two-dimensional electron gas (2DEG) at the interface of a semiconductor heterostructure. The method is based on the compensation of the *n*-type doping layer by an additional *p*-type layer in a structure similar to a Si/SiGe or GaAs/AlGaAs modulation-doped field-effect transistor. In the Si/SiGe material system the layer sequence is as follows: Si substrate and graded buffer, a relaxed undoped $Si_{0.7}Ge_{0.3}$ buffer, 20nm strained Si quantum well (QW), 10nm $Si_{0.7}Ge_{0.3}$ spacer, *n*-type $Si_{0.7}Ge_{0.3}$ layer, and as top layer the compensating *p*-type Si terminated by a Schottky barrier contact. A numerical calculation shows that total compensation of the doped layers, i.e. a depleted QW at zero temperature, can be achieved for an *n*-SiGe layer with d_n=14nm and N_D=3×10^{18}cm^{-3} by a *p*-Si, N_A=3×10^{18}cm^{-3}, of at least d_p=26nm thickness. Reducing the top-layer thickness by etching before the metal contact is deposited leads to a 2DEG in the QW which reaches a maximum density of n_S=4.9×10^{11}cm^{-2} at d_p=12nm. As d_p is further reduced n_S decreases, and at a remaining thickness d< 2nm the QW is depleted. If a step is etched into the *p* layer with a finite slope (e.g. by anisotropic etching) a lateral quantum well is confined underneath by the depleted areas without using any nanolithography. Combining two sloped steps forming a V-groove (now using nanolithography) we get two narrow parallel quantum wires. In the same way a deep pyramidal hole created by anisotropic etching is surrounded by a self-adjusting quantum wire ring, which should be much smaller than what is achievable with state-of-the-art lithographic techniques. This may be of interest for the fabrication of quantum interference devices.

CHARACTERIZATION OF ELECTRON AND HOLE ENERGY LEVELS IN SELF-ORGANIZED InAs/GaAs QUANTUM DOTS

P.N. Brounkov , N.N.Faleev, Yu.G.Musikhin, A.A.Suvorova, S.G.Konnikov, A.F.Tsatsul'nikov, A.Yu.Egorov, A.E.Zhukov, V.M.Ustinov, N.N.Ledentsov, P.S.Kop'ev, Zh.I.Alferov, D.Bimberg*

A.F.Ioffe Phys-Techn Inst.,26 Polytechnicheskaya Str., 194021 St-Petersburg, Russia

(*) Technische Universitat Berlin, Hardenbergstrasse 36, D-10623 Berlin, Germany

We propose a physical model to determine the allowed energy levels for electrons and holes in quantum dots (QDs). The model describes the capacitance-voltage (C-V) characteristics of semiconductor matrix containing a sheet of ordered QDs. The QD structures based on type-I InAs-GaAs heterostructure were grown by MBE on doped GaAs substrate and sandwiched between two doped GaAs region. The transformation of highly strained InAs layer on a lattice-mismatched GaAs buffer layer results in an array of coherent QDs with rather uniform shape and size. C-V characteristics of the Schottky barrier on the QD structures exhibit a step-like behavior. The region of the plato corresponds to the accumulation of majority carriers in the position of the sheet with QDs. The typical lateral size of a dot is smaller than 20 nm, providing a strong confinement in all three dimensions . It is suggested that the plane of uniform QDs can be considered as a set of non-interacting local centers with delta-function-like density-of-states. Steady state occupation of QD levels is determined by the Fermi-Dirac function depending on the relative positions of the quantum states and the bulk Fermi level. The simulation tool of C-V-characteristic is based on numerical solution of Poisson's equation. The model depends mainly on the following parameters : (i) electron (hole) energy levels in QDs, (ii) the sheet concentration of QDs, and (iii) the distance from the surface to the plane with QDs. The sheet concentration of QDs was determined from plain-view transmission electron microscopy (TEM) studies. The thickness of cap layer was derived from high resolution X-ray diffraction measurements. Thus, from the analysis of temperature dependent C-V characteristics we can extract the QD energy levels and the carrier occupation of QDs as a function of temperature. By using capacitance spectroscopy in p- and n-type doped matrix we have INDEPENDENTLY defined ground state electron and hole localization energies in QDs.

Inelastic Light Scattering from Electronic Excitations of Quantum Dots in a Magnetic Field

P. Hawrylak[a], D.J. Lockwood[a], P.D. Wang[b], C.M. Sotomayor Torres[c], A. Pinczuk[d] and B.S. Dennis[d]

[a]*Institute for Microstructural Sciences, National Research Council, Ottawa, Canada*

[b]*Dept. of Electrical Engineering, Notre Dame University, Notre Dame, IN, USA*

[c]*Nanoelectronics Research Centre, Glasgow University, Glasgow, UK*

[d]*AT&T Bell Laboratories, Murray Hill, NJ, USA*

The first inelastic light scattering experiments on deep-etched GaAs/AlGaAs modulation-doped quantum dots in a magnetic field are reported. The Raman measurements in magnetic fields up to 12 T and at large in-plane wave vector transfer reveal a multicomponent excitation spectrum of many-electron quantum dot samples of sizes from 100 to 200 nm. The three single particle transitions observed at zero magnetic field exhibit a complex behavior with magnetic field including splittings, crossings, and anticrossings. The experimental results are interpreted in terms of the calculated excitation spectrum in the Hartree approximation. The comparison of theory and experiment demonstrates the existence of an electronic shell structure within quantum dots and reveals a low energy excitation due to a Landau-like band crossing the Fermi level with increasing magnetic field.

Time Resolved Photoluminescence Studies of GaAs/AlGaAs Quantum Dots

N. Sai, B.Z. Zheng, X.P.Yang, W. Zhang, J.Z. Xu and Z.Y. Xu
National Laboratory for Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China
Fax: 86-10-2562389 E-mail: trzyxu@red.semi.ac.cn

Many methods either in process techology or material growth have been exploited to fabricate one or zero dimensional structures such as quantum wires and quantum dots. In this work, we present the investigation on GaAs/AlGaAs quantum dots realized by mask patterned implantion induced intermixing. In photoluminescence spectra, the QD structure is manifested by a low energy emission band due to the quantum dots and a high energy emission caused by the implanted lateral barrier. In the time-resolved PL measurements, we observed delayed luminescence rising time of QD compared to that of the reference quantum well, indicating a slow relaxation process of photo-generated carriers in the dots due to the reduction of phonon scattering rate in 0D system.[1] In addtion, the carriers of QD show a longer lifetime compared to that in the original quantum well. It is attributed to the efficient capture of the photo-excited carriers into the dots from lateral barrier which just surround the dots. The measured intensity ratio of I_{QD}/I_{QW} is estimated to be 3, in agreement with our prediction of the carriers capture from the barriesr into the dots. In the paper, the detailed kinetic of diffusion of carrier from the lateral barrier to the QD will be provided. We will also present the temperature dependence of the carrier life time in the QDs and give physical insight of our results.

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RESONANT TUNNELING THROUGH A SEMICONDUCTOR QUANTUM DOT

Kenji Natori and Nobuyuki Sano
Institute of Applied Physics, University of Tsukuba

The transport through a quantum dot weakly coupled with two electron reservoirs attracts attention both in the nanostructure physics and in the device application. We discuss the resonant tunneling through a semiconductor dot with spin-degenerate two levels. The dot is assumed to be controlled via capacitance coupling with the gate electrode. In order to clarify the transport characteristics for the structure, it is critical simultaneously to consider the electrostatic energy due to the capacitance, the discreteness of the energy spectrum as well as the Coulomb repulsion inside the small dot. The classical expression of the electrostatic energy includes the Coulomb repulsion as a portion. In our new approach, this portion is substituted by the quantal expression and the Anderson Hamiltonian for the resonant tunneling is derived. The Coulomb repulsion in the dot is effective between the electron pair with the anti-parallel spin. We have analyzed the case where the tunneling probability is small and finite bias voltages are applied to the system. The low temperature (but above the Kondo temperature) characteristics are studied. The mean field approximation is applied to the Hamiltonian. The transmission coefficient is evaluated by diagonalization of the Hamiltonian in the tight-binding formulation, and the resonant tunneling current is evaluated with the Landauer formula.
Each electronic state of the system is decomposed into both the right-incoming wave state and the left-incoming wave state, and each spin state in the dot has both these contributions. Without the Coulomb repulsion, the current simply steps up as the degenerate dot level crosses the Fermi level. The Coulomb repulsion introduces the energy separation between the up- and the down-spin levels and the current ramps up in two steps. These are the Coulomb staircase. A remarkable effect newly reported is that two different current states are allowed for the same bias condition in a restricted bias range. One is the current-flowing state where, for example, only the left-incoming wave portions for both the up- and the down-spin state in the dot are filled. The other is the no-current state where both the right- and the left-incoming wave portions are filled for the up-spin state, for example, and the down-spin state is empty. This brings about the hysteresis of the current-voltage characteristics when the tunneling barriers are asymmetric.

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Enhancement of Luminescence from Te Isoelectronic centers in ZnSTe/ZnS Quantum Dots

Allen Ng, I.K.Sou and W.K.Ge

Department of Physics, Hong Kong University of Science and Technology, Hong Kong

Y.S. Tang and C.M.Sotomayor Torres.

Nanoelectronic center, Glasgow University. United Kingdom.

Z.L.Yuan and Z.Y.Xu

Nations Superlattice Laboratory, Beijing, China

According to the report of Toshio Fukushima and Shigeo Shionya[i], isoelectronic centers Te_1, Te_2,... can be formed in ZnS:Te structures. The light emissions from Te_n centers are very efficient. They are predominant in the photoluminescence (PL) spectra, and can be excited directly by radiation absorption or through the energy transfer from Te_m to Te_n, where $m < n$.

In this work, nanometer-scale II-VI quantum dots, cut from molecular-beam epitaxy grown ZnS:Te/ZnS single quantum well heterostructure (QWs) by electron beam lithography and dry etching processing, are characterized by using the temperature dependent PL. It is found that the PL emission of the first Te isoelectronic center (Te_1) is significantly enhanced in comparison with that from the unprocessed region. We suggest that it is due to the fact that the non-radiative energy transfer is reduced because of the increasing of the surface area for the quantum dots structures. We also propose a simple model concerning the surface effect to understand such enhancement of the isoelectronic center related PL emission in quantum dots.

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Commensurability Oscillations by Runaway and Pinned Electrons

K.Tsukagoshi,[1,2,*] T.Nagao,[1] M.Haraguchi,[1] S.Takaoka,[1] K.Murase,[1] and K.Gamo[2]
[1]*Department of Physics, Faculty of Science, Osaka University*
Toyonaka, Osaka 560, Japan
[2]*Department of Electrical Engineering, Faculty of Engineering Science*
Osaka University, Toyonaka, Osaka 560, Japan

Commensurability oscillations are observed in the magnetoresistivity ρ_{xx} in the two-dimensional electron gas periodically modulated by strong repulsive potential "antidot". The origin of these oscillations is considered as the electrons chaotically traveling in the antidot lattice.[1,2] In this paper, we experimentally investigate details of the conductivity tensors.

Square antidot lattices with various aspect-ratio d/a, where d is the antidot diameter and a antidot period fixed to 1 μm, are prepared. The tensor of the magnetoconductivity σ_{xx}, which is deduced from the resistivity tensors observed in experiment, has a peak for small d/a, but do not has a peak for the large d/a near the magnetic field where the electron cyclotron diameter corresponds to the antidot period, although the pronounced peak of ρ_{xx} always appears. We ascribe the peak of magnetoconductivity σ_{xx} to the existence of the runaway electrons which skip over the antidot arrays. Then, because the runaway electrons are forbidden for the large d/a and disappear for the limit of small d/a, it is expected that the occurrence of runaway electrons has an optimum d/a. By using the experimental data sets of various d/a, we plot the dependence of σ_{xx} on d/a at the magnetic field of the pronounced peak of ρ_{xx}. The value of σ_{xx} has a peak under the change of d/a. On the other hand, it is found that the off-diagonal conductivity σ_{yx} always has dips at the peaks of ρ_{xx}. The dips inform of the existence of the pinned electrons which encircle around the antidots without collisions. Thus, σ_{yx} of the antidot lattice oscillates by the commensurate effect between the cyclotron diameter and the periodic scatterers. Consequently, the peaks of the commensurability oscillations of ρ_{xx} are determined by the existence of both the runaway electrons and the pinned electrons. Moreover, the relation between the absolute values of σ_{xx} and of σ_{yx} also correlates with the peaks of ρ_{xx} through the relation of $\rho_{xx} = \sigma_{xx}/(\sigma_{xx}^2 + \sigma_{yx}^2)$. From the above consideration, we can explain all the peaks of the commensurability oscillations of ρ_{xx} in any square antidot lattice.

*Present address: Cavendish Laboratory, Department of Physics, University of Cambridge, Madingley Road, Cambridge, CB3 0HE, UK

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ABSTRACT

Two -Dimensional Clusters in SiGe/Si Superlattices and Their Effect on Field Effect Transistor Transport Characteristics

D .Girginoudi and A. Thanailakis
Democritus University of Thrace, Xanthi Greece
and
A. Christou
University of Maryland, College Park, MD

Superlattices of $Si_{.80}Ge_{.20}$/Si (100) were grown by pulsed laser deposition consisting of alternating 10nm SiGe and silicon layers and a total of 10 periods. The presence of alloy clustering at SiGe/Si interfaces were investigated by photoluminescence and using dynamical scattering theory and Monte Carlo simulation. Photoluminescence line broadening indicated the presence of Ge rich clusters (2-3nm) in layers grown at a substrate temperature of 600°C using an excimer laser at 248 nm wavelength.

The 2D clusters were modeling, assuming a spherical shape and a potential of the form $\delta \Delta u$ where δ is the composition variation and Δu is the disorder potential. A scattering matrix element was derived which included intraband scattering. Transport effects were calculated using Monte Carlo techniques. Of interest was lateral transport in a field effect transistor configuration. Therefore, velocity versus field curves were calculated where electron motion is confined to the 2-D like SiGe layers. Using concepts of charge control, current versus voltage relationships were derived. The derived models showed that for the case of a 250 um conducting channel lateral length with 2D clusters evenly placed at every 10 nm, the transconductance increase is 25 percent and is a function of both cluster size and separation.

In order to measure the effect of clustering, high electron transistors were fabricated with two conducting 2D channels consisting of Si/SiGe/Si grown on high resistivity (100) silicon. Using 0.5 um gates, a transconductance of 125 ms/mm was obtained in transistors without alloy clustering which decreased to less than 80 ms/mm when alloy clustering was present. The present investigation has related the presence of 2D nano-clusters to device performance and has also shown agreement between the experimental results and theoretical calculations.

LOW-TEMPERATURE TRANSPORT REGIME IN 3-DIMENSIONAL LATTICE OF QUANTUM DOTS

S.G.Romanov, A.V.Fokin, D.V.Shamshur

Ioffe Physical Technical Institute, Polytekhnicheskaya st., 26,194021, St.Petersburg, Russia

D.K.Maude*, J.C.Portal*

*GHMFL, MPI-CNRS, F38042, Grenoble and INSA-Toulouse,31077, France

We have investigated 3D lattices of weakly coupled quantum dots (QDs) designed by structural confinement of InSb and Te in empty voids of a quasi-crystalline opal. The diameter of the QDs is in the range 80-120nm depending on the particular opal matrix and the density of dots is around $10^{14}cm^{-3}$.

The high-T resistance of the dot lattice is dominated by the transparency of the tunnel barriers between QDs. At T<50K for samples with carrier density below $10^{15}cm^{-3}$ (opal-InSb) the homogeneous current distribution reduces to several percolation paths, since non-penetrable Coulomb barriers are built up between dots statistically occupied by free electrons. Correspondingly, the dimensionality reduces from 3D to 1D. The Fermi wavelength, which in the 3D regime exceeds the dot size, is much smaller in the 1D regime , i.e. the scattering on the dot-matrix interface becomes essential. This leads to the anomalous shape of magnetoresistance and Hall resistance traces because of carrier wave-guiding effects. Anomalous R_{xy} curves were also found for opal-Te, but for the 3D regime the low λ_F is provided by then high carrier concentration.

The low-T voltage dependence of the resistance exhibits a temperature-dependent maximum. The resistance drop at low voltage corresponds to increasing of λ_φ and the drop at high bias - to increasing of the system dimensionality. The fine structure superimposed on this background may relate to commensurability of λ_φ with the lattice spacing. The shape of R_{xx} changes with the voltage, since it probes different current configurations of the same QDs ensemble. The long-range variation of R_{xx} is accompanied by a short range reproducible quasi-periodical fluctuations of UCF type. These fluctuations are stable even when the bias current is increased by two orders of magnitude, but changes upon temperature cycling. Such a mesoscopic behaviour is consistent with a few percolation paths remaining for the current transfer in this regime.

Size quantization patterns in self-assembled InAs/GaAs quantum dots

F. Bogani, L. Carraresi, R. Mattolini and M. Colocci
Dipartimento di Fisica-INFM and LENS, Largo E. Fermi 2, 50125 Firenze, Italy
A. Bosacchi, S. Franchi and P. Frigeri
CNR-MASPEC, Via Chiavari 18/A, 43100 Parma, Italy
S. Taddei
Dipartimento di Fisica, Universita' di Firenze, Largo E. Fermi 2, 50125 Firenze, Italy

Molecular beam epitaxy has been used for growing self-assembled InAs quantum dots (QD) on GaAs substrates. A continuous variation in one direction of the InAs average coverage has been obtained by properly orienting the GaAs substrate with respect to the molecular beams. Preliminary data obtained by AM and ST microscopy show the formation of dome-like structures with base diameters around 15±5 nm and heights roughly around 1.5±0.5 nm.

We have exploited the high photoluminescence (PL) efficiency of the QDs for a detailed optical characterization of the dot assemblages.

Narrow PL bands (20-25 meV FWHM) peaking at emission energies decreasing from about 1.4 eV to 1.25 eV for increasing InAs coverage from roughly 1.5 to 2.2 monolayers have been observed even after excitation of a large number of dots (laser spot diameter of the order of 100 μm) with photons of energy greater than the GaAs bandgap.

A clear quantization of the dot sizes is observed from the distinct PL bands separated in energy by an average spacing of 20-30 meV; a consistent phenomenology has been also obtained with near resonant excitation of the QDs.

Additional information on the carrier relaxation and recombination in these structures has been obtained by means of time-resolved PL measurements with ps resolution; in fact , both the relaxation within single dots and the transfer of excitation between different dots have been investigated.

The possible origins of the size quantization patterns observed have been discussed within a theoretical model for the electronic states in the QDs that takes into account strain, together with the characteristic relaxation and recombination time constants.

Intrinsic and Extrinsic Photo- and Electro-Luminescence in Si Nanostructures

L. Tsybeskov, K.D. Hirschman, S. P. Duttagupta, K. L. Moore, D.G. Hall, and P.M. Fauchet

Department of Electrical Engineering and The Institute of Optics, University of Rochester
Rochester, NY 14627, USA

Porous silicon (PSi), a form of Si containing nanocrystallites passivated by Si-H bonds, photoluminesces efficiently in the visible due to quantum confinement. PSi has not been integrated in conventional Si process technology because it does not survive standard processing steps. In this presentation, we demonstrate that silicon-rich silicon oxide (SRSO) produced by high temperature oxidation of PSi is a stable, efficient light emitting material. We show that SRSO is a novel nanocomposite material consisting of Si nanoclusters and an oxide tissue that can be processed and doped to produce strong, room-temperature photoluminescence (PL) and electroluminescence (EL) from the blue to past 1.5 μm.

When the oxidation is performed at a temperature $T < 900^{o}C$, the intrinsic PL of SRSO is the familiar visible band due to quantum confinement in Si nanocrystals, as confirmed by resonant PL measurements. When $T > 900^{o}C$, the intrinsic PL is in the infrared near 1.15 μm. The low-temperature PL spectrum shows that this luminescence is due to phonon-assisted band-edge recombination within large Si grains that are formed during the heat treatment, as the melting point of Si nanocrystals is much lower than bulk Si. The most striking result is that the integrated PL spectrum is temperature-independent. When $T > 950^{o}C$, the red/infrared PL disappears, consistent with the production of a porous glass.

SRSO can be doped with a large number of impurities, using electroplating or implantation. SRSO implanted with S and Se exhibits room temperature PL near 1.4 μm and 1.2 μm respectively. SRSO electroplated with Er^{+} and Nd^{+} is strongly luminescent at 1.54 μm and 1.06 μm respectively. Compared to Er^{+} doping of PSi, we find that the PL spectrum is free from a broadband background that can be associated with dangling bonds in the PSi matrix. The preparation and processing parameters that control the PL intensity and spectrum will be discussed.

Using conventional Si processing steps, we have manufactured light-emitting devices (LEDs) that produce EL in the same spectral range as the PL. Our best devices to date have a threshold at 2 V, emit up to 1 mW/cm^2 of EL, do not show any sign of degradation for weeks of continuous operation and have a power efficiency of ~0.1%. These results depend on efficient carrier injection and transport in the SRSO layer and on large quantum efficiency.

Optical Properties of Vertically Aligned Self-assembled InGaAs Quantum Dots Layers on (311)A/B and (100) GaAs Substrates

P.P. González-Borrero, D.I. Lubyshev, E. Marega Jr., and P. Basmaji

Instituto de Física de São Carlos-Universidade de São Paulo

CP 369, CEP 13560-970, São Carlos, SP, Brazil

Vertically self-organized growth of InAs islands separated by GaAs spacer layer has been reported in molecular-beam epitaxy (MBE) on (100) GaAs substrates[1]. In this work, we present substrate orientation effects on optical properties of vertically stacking $In_{0.5}Ga_{0.5}As$ layers grown by MBE on (311)A/B and reference (100) GaAs substrates mounted on the same substrate holder. For quantum dots (QD) formation, 6 monolayers (ML) of $In_{0.5}Ga_{0.5}As$ were deposited for (100) plane. Then, GaAs spacer layers were deposited. Growth interruption during 3 min. before and after $In_{0.5}Ga_{0.5}As$ depostion, was carried out. In order to provide the vertically collinearity of the islands, this combination of 6 ML $In_{0.5}Ga_{0.5}As$ and GaAs spacer layer was repeated 10 times. Samples were grown for different GaAs spacer thickness. The spacer thickness variation shows influence in PL spectra for all planes. Difference on peak shape, peak position, amplitude and integral luminescence has been observed for all surfaces. These differences suggest that the In migration on the spacer layer caused by the strain fields induced in the spacer layer by the islands buried below, is different in the three surfaces. Vertical electronic coupling between QD is confirmed by photoluminescence (PL) temperature dependence. Low temperature PL measurements indicate the presence of non-vertically aligned $In_{0.5}Ga_{0.5}As$ QD principally on (311) surfaces.

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LO-PHONON ASSISTED RELAXATION OF HOT EXCITONS IN CdZnSe/ZnSe QUANTUM WELLS AND QUANTUM DOTS

R. Spiegel, G. Bacher, and A. Forchel, [1]B. Jobst, [1]D. Hommel, and [1]G. Landwehr

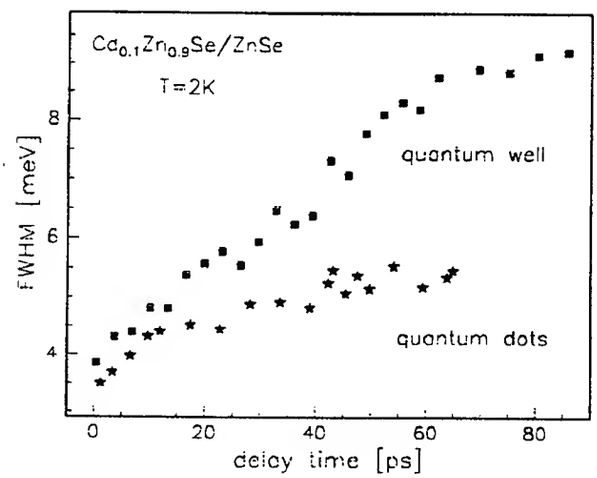
Technische Physik, [1]Experimentelle Physik III, Universität Würzburg, Germany

FAX: +49-931-888-5143 EMAIL: spiegel@wpfx32.physik.uni-wuerzburg.de

Hot exciton relaxation was studied in CdZnSe/ZnSe quantum dots and quantum wells by time-resolved photoluminescence spectroscopy using a frequency doubled Ti-Sapphire laser pulse for excitation and a streak-camera for detection. Low exciton densities ($< 5 \cdot 10^7$ cm^{-2}) are generated to suppress the influence of exciton-exciton scattering.

For excitation energies corresponding to an integer number of the longitudinal-optical phonon energy above the excitonic resonance, a drastical linewidth narrowing of the exciton emission peak from 10 meV to < 4 meV is observed immediately after the excitation pulse. This can be explained by a phonon assisted generation of hot excitons and a subsequent fast relaxation process due to LO-phonon scattering, creating an energetically narrow exciton distribution within the inhomogeneously broadened exciton band.

In quantum wells, a distinct broadening of the exciton line with increasing delay time was observed (see figure). This indicates the spatial diffusion of excitons into energetically lower localized states. The decrease of the typical low temperature time constant of 100 ps to a value of about 30 ps for T = 40 K is consistent with an acoustic phonon assisted exciton migration in the well.



To suppress the lateral diffusion of the excitons, quantum dots with a diameter of about 35 nm were realized by using a lithographic technique. Compared to the quantum well, we observe a drastic reduction of the linewidth broadening with increasing time (see figure), indicating the spatial confinement of excitons in quantum dots.

Flux confinement by regular arrays and clusters of antidots in Pb/Cu bilayers

E. Rosseel, T. Puig, M. J. Van Bael, M. Baert, R. Jonckheere(*), V.V. Moshchalkov and Y. Bruynseraede

Laboratorium voor Vaste-Stoffysica en Magnetisme, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium

(*)*Interuniversity Micro-Electronics Center, Kapeldreef 75, B-3001 Leuven, Belgium*

ABSTRACT

We have studied the magnetoresistance of superconducting films with an antidot array (period = 1μm, typical diameters: 0.2μm→ 0.7μm) and mesoscopic antidot clusters of 2μm*2μm with only four antidots (diameter ≈ 0.47μm). Both kind of systems were written in positive PMMA e-beam resist onto SiO_2 substrates. The Pb/Cu bilayers were e-beam evaporated in an MBE apparatus onto the liquid N_2 cooled substrates at a pressure of 5 10^{-8} Torr. After lift-off, a thorough characterization was performed using x-ray diffraction, scanning electron microscopy and atomic force microscopy.

For both the clusters and the arrays, characteristic minima have been observed in the magnetoresistance which are caused by the existence of certain vortex configurations, minimizing the vortex-vortex interactions. By comparing these data with calculations carried out in the London limit $|\psi| \equiv const$, valid close to the superconducting transition temperature, several vortex configurations have been identified.

This work is supported by the Belgian National Fund for Scientific Research (NFWO), the Interuniversity Attraction Poles (IUAP) Programs, the Flemish Concerted Action (GOA) Programs and the European Program for Training and Mobility of Researchers.

Microstructuring of Si(100) with light-induced Dry Etching in the VUV

U. Streller, A. Krabbe and N. Schwentner

FU Berlin, Institut für Experimentalphysik, Arnimallee 14, D-14195 Berlin, Germany
Tel.: +49 -30 838 6233 Fax: +49 -30 838 3050 E-mail: streller@omega.physik.fu-berlin.de

Direct writing on Si without photoresists provides an attractive way for the fabrication of Si based VLSI structures. Light induced dry etching of Si(100) using synchrotron radiation (SR) in the VUV range and a halogen containing gas (XeF_2) has been investigated with respect to selectivity, anisotropy, quantum efficiency, optimal wavelength, spatial resolution and quality of the photochemical etching processes. The samples are exposed to a continuous gas flow and radiation from a 3m normal-incidence monochromator at the synchrotron BESSY (Germany) either wavelength selected with the first order of dispersed light or by different filters for the grating in zeroth order. The etched replicas of a special mask on the Si(100) surface were observed by optical, scanning electronic, scanning force and interference microscopy.

We succeeded in a very strong suppression of the spontaneous reaction by addition of several buffer gases (He, Ne, Ar, O_2) to XeF_2 without blocking the photon-induced etching. Typical for the etching process is the high selectivity and quality of the etched structures. The achieved sub-micrometer lateral resolution of the etched replica is only diffraction limited.

The absolute quantum efficiency of the etching is strongly wavelength dependent and reaches a value of 10 removed Si atoms per incident photon at 120 nm. This very high efficiency, which exceeds that in the visible spectral range by more than four orders of magnitude, is attributed to a selective electronic excitation of a thin fluorosilyl layer on top of the Si wafer combined with an amplifying chain reaction.

Single-electron tunneling in granular Ag-SiO_2 films

Minoru Fujii, Takeshi Kita, Shinji Hayashi * and Keiichi Yamamoto *
The Graduate School of Science and Technology,
* Department of Electrical and Electronics Engineering, Faculty of Engineering,
Kobe University, Rokkodai, Nada, Kobe 657, Japan.
FAX:+81-78-861-7679, e-mail: fujii@gradura.scitec.kobe-u.ac.jp

The Coulomb blockade (CB) and Coulomb staircase (CS), which arise from single-electron tunneling (SET), have recently attracted much interest. The SET has mainly been studied for double barrier tunnel junction geometry, where a small metallic island is coupled to electrodes via two tunnel junctions. The SET has also been observed for granular metal-insulator films. In the granular films, since small metal particles are randomly dispersed in dielectric films, the conduction path consists of very large number of parallel arrays of tunnel junctions. Until now, the observations of CB and CS in granular films were only made using low-temperature scanning tunneling microscopy (STM), because the CB and CS may be smeared out by averaging over many conduction paths.

In this work, we have succeeded in observing distinct CB and CS structures in granular Ag-SiO_2 films without STM. The thin Ag-SiO_2 films about 12nm in thickness were prepared by co-sputtering of SiO_2 and Ag on glass substrates. The average diameter of Ag particles in granular films was about 3-4nm. The upper and lower electrodes were Al stripes 100μm wide and 100nm thick. The active device area was $100 \times 100\mu m^2$.

Figure 1 shows a typical I-V characteristic observed. We can clearly see CB and CS structures. The most interesting feature seen in Fig.1 is that the height and steps of the CS structures are not uniform. In particular, the CB region is extended up to 0.1V and much larger than the CS steps. The observed I-V characteristics could not be explained by simple double barrier tunnel-junction models. Much more complex tunneling paths, such as the transport of electrons via more than two particles, should be taken into account in accounting for the observed I-V characteristics.

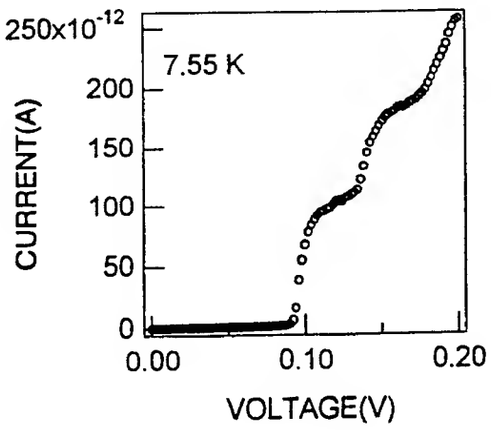


Fig. 1 I-V characteristic of granular Ag-SiO_2 film

SCANNING TUNNEL MICROSCOPY OF FULLERENE MONOLAYERS.

V.A.Fedirko, Moscow State University of Technology "Stankin", Moscow, Russia;
V.A.Bykov, M.D.Eremchenko, Research Institute of Physical Problems, Zelenograd, Moscow, Russia.

The results of the tunnel electron microscopy investigation of C_{60} fullerene monolayers are presented. A fullerene monolayer is formed on a highly oriented pyrolytic graphite wafer by the Shaefer method using surfactant - fullerene mixture. The surfactant is used as a matrix and a fullerene Langmuire - Blodgett monolayer is so deposited.

Scanning tunnel electron microscopy with extremely small tunnelling current of the order of 10^{-10} A the shows the regular surface structure of fullerene molecules. The rhombic two - dimensional lattice is distinctly observed with some substructure inside each cell. The different substructures may result from the fact that the surfactant does not rigorously determine the orientation of a fullerene C_{60} molecule.

Tunnel electron spectroscopy measurements have been also carried out in -2,0 +2,0 V bias interval. The results may be interpreted in terms of single electron tunnelling. Coulomb blockade effect is observed in good accordance with the tunnel junctions capacitance estimations. Some fine structures of current - voltage characteristics are also observed which may be connected with the complex electron spectrum structure of a monolayer.

Corresponding and presenting author
Valeri Fedirko
Moscow State University of Technology "Stankin"
3a Vadkovski per.,
Moscow, 101472, Russia.

Friday

FrA Spectroscopy of silicon nanostructures

Manipulation of C_{60} molecules on a Si surface

Y-R. Ma, A.W. Dunn, M.D. Upward, P. Moriarty and P.H. Beton

Department of Physics, University of Nottingham, Nottingham NG7 2RD

We have used an ultra-high vacuum (UHV) scanning tunnelling microscope (STM) to image and manipulate C_{60} molecules absorbed on a Si(111)-7×7 surface. At low coverage ($\sim$0.01 monolayers) molecules are absorbed at random sites; however, for coverages close to a monolayer they are partially ordered in a hexagonal arrangement. Second and higher layer islands are observed at higher coverage in which the molecules have a high degree of hexagonal order. These islands may be desorbed by annealing in the range 200-300°C, leaving a Si surface terminated by a C_{60} monolayer which inhibits oxidation of the Si(11) under exposure to atmosphere.

It is possible to modify these layers in a number of different ways. Individual molecules may be manipulated to form simple patterns at low coverage. For higher coverage nanometre scale clusters may be formed and for multilayer coverage complete islands may be manipulated. In addition we show that vertical growth of C_{60} layers may be initiated by the STM. Many of these results have been reproduced on the clean Si(110) surface. Finally we discuss the potential of this material system for nanoscale fabrication.

Dynamical STM Studies of the Growth of Ge or Si on Silicon by MBE

M. Kästner and B. Voigtländer
Institut für Grenzflächenforschung und Vakuumphysik
Forschungszentrum Jülich, 52425 Jülich

A high teperature scanning tunneling microscope (STM) capable of imaging during MBE growth is described. We studied the epitaxial growth of germanium or silicon on silicon at 600 - 900 K sample temperature *in vivo*. This technique gives acces to the dynamics of the growth process on an atomic scale. The potential of the method is demonstrated by the following results.

Si/Si Homoepitaxy

- A transition from initial multilayer growth to pure layer by layer growth was imaged in Si/Si(111) homoepitaxy. It can be explained by a different concentration of defects in the substrate and the epitaxially grown layers.
- The details of nucleation have been observed at two-dimensional (2D) islands in Si/Si(111) homoepitaxy. We observed sharpening of the initially rounded corners, growth in stripes of of one half unit cell width along the edges and facets of different growth speeds. A model of hindered nucleation on the faulted part of the 7x7 reconstruction explains the experimental results.

Ge/Si Heteroepitaxy

- The layer by layer growth of the two-dimensional Stranski Krastanov layer of Ge on Si(111) and the formation of 3D islands during further growth was observed. An inversion of the aspect ratio of the islands with increasing coverage indicates a transition from coherent to dislocated islands.
- The transition from layer by layer growth to 3D islanding was imaged. Nucleation of a 3D island was observed, showing that nucleation does not necessarily occur on top of the higest protrusions in the wetting layer.
- After 3D islands have formed, mass transport from the wetting layer to the 3D islands sets in, partially breaking up the initially (nearly) closed wetting layer.
- The fact that 3D islands act as strong atom sinks is also illustrated by an experiment showing the evolution of 2D islands on the wetting layer after evaporation was stoped. Theese 2D islands do not undergo Ostwald ripening in the sense that the bigger ones grow at the expense of the smaller ones. The 2D islands rather decay completely. We conclude that their mass is transferred to the 3D islands.

SiO_2 and Si nanoscale patterning with an atomic force microscope

B. Klehn and U. Kunze

Lehrstuhl für Werkstoffe der Elektrotechnik, Ruhr-Universität Bochum,

D-44780 Bochum, Germany

We report on a nanolithography process consisting of the deformation of a thin photoresist layer due to the repulsive force at the tip of an atomic force microscope (AFM) and a pattern transfer by wet chemical etching. Si(100) wafers with 10nm thermally grown oxide were coated with a diluted spun-on resist layer of about 5nm thickness. After a one-minute bake at 95 °C in air the sample is mounted in the AFM (Nanoscope III, Digital Instruments) having 100×100 μm^2 usable writing field. The lithography is performed by a vector scan using the "tapping mode", where the tip executes a vibrating move of several hundred kHz against the surface. We used a FIB-sharpened Si tip with 10nm radius of curvature. The desired resist pattern consisting of trenched lines of arbitrary direction and length is generated by the lithography tool that is included in the AFM software. The main parameter is the drive amplitude which excites the cantilever vibration. Switching on a sufficiently high driving amplitude leads to a penetration of the resist by the tip down to the oxide surface. Pattern transfer into the oxide by etching in buffered HF results in typically 20-40 nm (or even less) wide grooves (Fig.1). Alignment of lines along the [110] directions allows the etching of V grooves into the Si substrate by anisotropic KOH etching (Fig.2: 200nm period, 50nm top width, oxide removed).

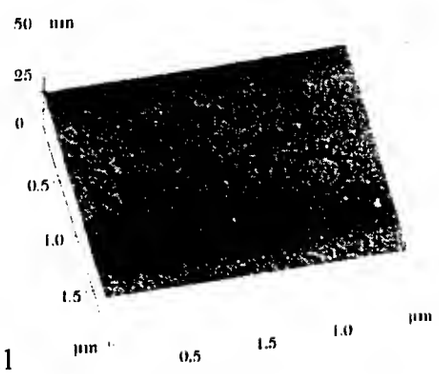


Fig.1

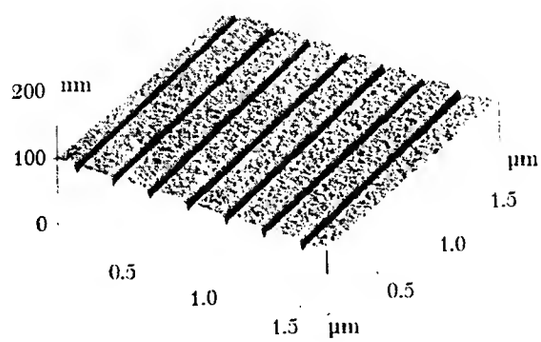


Fig.2

On the Origin of Blue Light Emission from Ge-Nanocrystalls Containing a-SiO_x Films

R. Weigand, M. Zacharias, J. Bläsing, P. Veit and J. Christen
Institut für Experimentelle Physik, Otto-von-Guericke Universität Magdeburg, PF 4120, 39016 Magdeburg, Germany

Quantum Size effects in superlattices and other low dimensional structures based on indirect semiconductors like Si and Ge are reported in recent publications [1] and made responsible for the optical properties of these nanostructures. However, no unambiguous evidence for Quantum Confinement being the origin of luminescence is presented so far. For example no correlation between the size of the quantum dots and an significant change of the low-dimensional bandgap is found, in contrast to the most fundamental theoretical prediction for quantum confinement [2].

Here we present results of a comprehensive systematic investigation on structural and optical properties of a series of Ge nanocrystal containing a-SiO_x films. The Ge fraction of these films, prepared by dc-magnetron sputtering, is precipitated as amorphous nanosize clusters. Their size distribution is determined by the preparation parameters, e.g. sputtering power and substrate temperature. The size of the clusters is obtained by SAXS, yielding a logarithmic normal distribution with average size from 13^{+7}_{-3}nm down to 4^{+5}_{-2}nm. The transformation of the Ge-Clusters into nanocrystallites is induced by thermal annealing at temperatures of 700°-800°C. After annealing X-ray diffraction confirms the complete crystallization of the previously amorphous Ge clusters. This crystallization process goes along with an intrinsic cleaning and reconstruction of the growing crystals. Structural changes as well as changes in chemical binding are monitored by IR- and Raman-spectroscopy. The resulting size distribution of the Ge nanocrystalls measured by X-ray diffraction and HRTEM is found to be the same as the original cluster size distribution. Bright blue room temperature photoluminescence (excitation: 325nm, HeCd laser) is observed from the films with spectral maxima at wavelengths of 410±10nm and 540±20nm whose relative intensities strongly depend on annealing conditions. Despite of a systematic variation of the average size of the Ge crystallites by a factor of 3, the two PL bands show no systematic energy shift. Therefore our results are *not* in agreement with a quantum confinement origin of the room temperature PL. However, a clear correlation of the PL bands with the presence of the crystals is strongly evidenced. Considering the crystallization process with its enrichment of highly disturbed bindings in the inhomogeneous strain field of the Ge surface we propose the twofold coordinated O-Si-O (Si_2^0) and O-Ge-O (Ge_2^0) respectively, as a probable origin for the blue luminescence [3]. A similar luminescence in Ge doped glassy SiO_2 is reported in [4]. Detailed PL investigations suggest a spin forbidden transition at the defect as the origin of the blue luminescence of the Ge nanocrystalls.

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Visible Luminescence in Si/SiO_2 Superlattices

D.J. Lockwood, B.T. Sullivan, P.D. Grant, A. Blais, Z.H. Lu, J.-M. Baribeau, H.J. Labbé

and J. Stapledon

Institute for Microstructural Sciences, National Research Council, Ottawa, ON, Canada K1A 0R6

Amorphous Si/SiO_2 superlattices with numbers of periods ranging from 6 to 525 and periodicities between 2 and 5 nm have been grown on (100) Si wafers by several different techniques: molecular beam epitaxy, magnetron sputtering, and plasma enhanced chemical vapor deposition (PECVD). With the first two methods little or no hydrogen was incorporated during growth and visible photoluminescence (PL) was obtained at wavelengths from 520 to 800 nm. The shift in the PL peak position with Si layer thickness was consistent with quantum confined emission.[1] Annealing the sputtered superlattices at temperatures up to 1100°C produced very bright red PL, similar in intensity to that observed in porous Si samples.[2] The PL was also considerably enhanced by deposition on aluminum-coated glass substrates. For large numbers of periods (e.g., 425) the PL was strongly modulated in intensity owing to optical interferences within the superlattice. Similar quantum-confined PL was also observed in the PECVD grown superlattices, where the amorphous Si layers were heavily hydrogenated. Green cathodoluminescence was observed from 100-period sputtered superlattices.

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FrB Quantum devices

Digital Single-Electronics: Progress and Problems

Alexander N. Korotkov

Nuclear Physics Institute, Moscow State University, Moscow 119899, Russia
and
Department of Physics, State University of New York, Stony Brook, NY 11794-3800

Tunneling of single electrons has been thoroughly studied both theoretically and experimentally during last ten years. By the present time the basic physics is well understood, and creation of useful single-electron devices becomes the important issue. Single-electron tunneling seems to be the most promising candidate to be used in the future integrated digital circuits with the typical size scale of few nanometers and below.

Many proposals of single-electron memory and logic devices have been put forward. Conceptually the simplest way is to use Single-Electron Transistors (which consist of two tunnel junctions in series and the capacitively coupled gate) instead of FET transistors in circuits resembling conventional electronics. The drawback of this approach is the nonvanishing static current through transistors. Despite the power consumption per transistor can be very small, on the order of 10^{-9} W, it is unacceptably large for the densities about 10^{11} cm^{-2}. This problem can be circumvented in another type of single-electron logic/memory circuits which code information by the presence or absence of an extra electron on a particular conducting island. The prototype memory cells of this type were demonstrated recently using three different technologies (based on Al, GaAs, and Si). Logical gates of this type are more difficult to implement because it requires the control of single electrons by single electrons and effective amplification of the signal, and so far they have not been experimentally verified. Single-electron logic can be made "wireless" with the power supplied by alternating electric field (this feature is quite important at the size scale of few nanometers). In the recent suggestion of Single-Electron Parametron the rotating electric field plays simultaneously the role of the power supply and the global clock. The energy dissipation in this device can be less than k_BT per logical operation, that makes 3D integration possible in principal.

There are two main obstacles on the way to practical digital single-electronics. First, the maximum operation temperature of devices is on the order of 0.01 e^2/C. This means that 77K operation would require $C<3\cdot10^{-19}$ F that corresponds to very small size scale (about 1-2nm). However, the operation of simple single-electron "devices" at 77K and even at room temperature has been already reported by several groups. One can hope that the necessary small-size technology will be eventually available. The second obstacle is the sensitivity of single-electron devices to sub-electron fluctuations of the background charge induced by nearby impurities. However, even if this problem will not be solved technologically, some integrated circuits are still possible, for example, the recently suggested Background-Charge-Independent Single-Electron Memory. So, despite of difficulties, Single-Electronics has a real chance to be the basis of future ultradense integrated circuits.

HIGH TEMPERATURE SINGLE-HOLE SILICON TRANSISTORS

N.T.Bagraev*, W.Gehlhoff**, L.E.Klyachkin* and A.M.Malyarenko*

*A.F.Ioffe Physico-Technical Institute, St.Petersburg, 194021, Russia

**Technische Universität Berlin, Arbeitsgruppe EPR am Institut für Festkörperphysik, Rudower Chaussee 5, D-12484 Berlin, Germany

We present high temperature (77K, 300K) single-hole transistors, for the first time, based on silicon diffusion nanostructures. This is made possible by utilizing a quantum wire with isolated quantum dots, which is formed naturally inside ultra-shallow silicon p-n junctions using non-equilibrium diffusion processes.

By varying the parameters of the surface oxide layer and diffusion temperature (800^0 C-1100^0 C), it was possible to define the criteria leading to the fabrication of the ultra-shallow p-n junctions (5 nm - 30 nm), the depth of which was controlled using the SIMS technique. The cyclotron resonance investigations and current-voltage characteristics show that the p-n junctions obtained consist predominantly of natural longitudinal or lateral quantum wells (LQW, LaQW) as a function of diffusion temperature. The quantized conductance findings obtained at 77K and 300K have revealed quantum wire systems that are formed inside LQW and LaQW because of the electrostatic confining potential induced by strong charge correlations.

The nanotechnology suggested enables to obtain ultra-shallow p-n junctions and n-p-n transistor structures that represent the combinations of crystallo-graphically oriented quantum wires and dots with capacitances up to 10^{-19}F, which are enough to observe the charging effects of single holes at high temperature. The room temperature field-effect and bipolar transistors which contain the multiple-tunnel dot inside the isolated quantum wire reveal Coulomb staircase, evidence supporting operation of a single-hole transistor, when the gate voltage is near the threshold voltage. Periodic current oscillations as a function of the gate voltage, which are due to single-hole charging effect, have been also observed.

Distinct Two-Dimensional Carrier Injection Phenomena in Extremely Thin SOI Insulated-Gate pn-Junction Devices: Prospect of New Device Applications

Y. Omura
NTT LSI Laboratories, 3-1, Morinosato Wakamiya, Atsugi 243-01, Japan

This paper describes distinct quantum-mechanics-based carrier-injection phenomena in SOI pn-junction devices experimentally and theoretically. Reduction of the silicon layer thickness significantly influences the nature of carrier transport characteristics: It results in the two-dimensional (2-D) quantization of the conduction, and the transconductance characteristics of MOSFET/SOI show step-like anomalies [1, 2]. These step-like anomalies are found experimentally not only in MOSFET/SOI (majority-carrier devices), but also in SOI pn-junction devices (minority-carrier devices) [3]. Additionally, oscillation-like anomalies are also found experimentally at a high gate electric field in the SOI pn-junction devices [3].

Numerical simulations suggest that these two types of anomalies reflect the density of states of the injected carriers in the injected region. Simulations also indicate that the oscillation-like anomalies, which are not found in MOSFET/SOI, reflect the change, from electrons to holes or from holes to electrons, of the carrier type predominantly injected.

New findings obtained from the theoretical formulation can be summarized as follows.

(i) The concept of the intrinsic carrier concentration in the 3-D system still holds in the 2-D system. The concept of the pn product keeps its conventional meaning especially in the low-level injection. Therefore, the injection of either type of carrier is controlled by the concentration of the other type of carrier. In the injection under a high gate electric field, however, the concept of the pn product breaks down and the conventional transition region is dimmed by the gate electric field.

(ii) An effective increase in the forbidden band-gap energy occurrs through the 2-D quantization of the system [4]. The intrinsic carrier concentration in the 2-D system is much smaller than that in the 3-D system. Hence, the injection across the junction is suppressed through the effective reduction of both the density of states of carriers and the intrinsic carrier concentration.

(iii) The diffusion length of the minority carriers depends strongly on the gate voltage, and the internal electric field across the junction can be controlled by the gate electric field. In other words, this phenomenon is applicable to new injection-control quantum-effect devices, such as the surface-tunnel transistor [5].

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One dimensional and two dimensional phenomena in Silicon-On-Insulator (SOI) MOSFET devices

X. Baie*, J.P. Colinge*, V.Bayot**, and E.Grivei**

Université Catholique de Louvain

(*) DICE, Place du Levant 3, 1348 Louvain-La-Neuve, Belgium

(**) PCPM, Place Croix du Sud 1, 1348 LLN, Belgium

Thin silicon films insulated from bulk silicon by a buried SiO_2 layer are a good based material for quantum devices fabrication. In this top 40-to-120nm thin layer Gate-All-Around (GAA) transistor as well as a quantum wire array have been realized and measured at low temperature. The GAA MOSFET show 2DEG effects in his transconductance curve. This measurement have been correlated by self-consistent energy levels simulation and this for different confinement ticknesses. The e-beam lithography gives the ability to go one step further and quantum wires MOSFET have been realized. As expected the transconductance characteristic show stairway-like which are characteristic of a 1DEG structure. A finite element method simulator has been used to solve the self-consistent problem of the Poisson and Schrödinger equation, density of state distribution in the cross section of this kind of wires. For differents gate voltage waves functions as well as energy levels, electron concentration and potential distribution can be evaluated. This show, for low gate voltage values a degeneracy of first wave functions and the variation of the energy levels. Computed energy levels and bands filling agree well with low-temperature measurement made on the wires.